ECLIPSES OF THE SUN

MITCHELL

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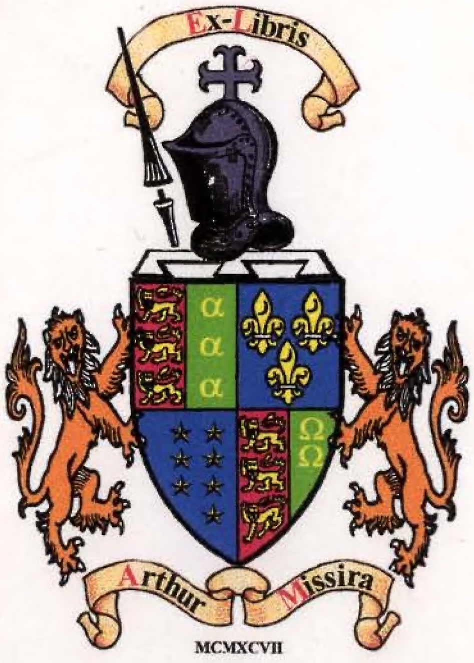

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Total Eclipse of the Sun, June 8, 1918.

From the painting by Howard Russell Butler, N. A.

The corona and prominences as observed through thin clouds at the United States Naval Observatory Station, Baker, Oregon. (Original size of painting 49 x 33½ inches).

ECLIPSES OF THE SUN

BY

S. A. MITCHELL

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TO MY FRIEND
EDWARD DEAN ADAMS
THIS BOOK IS AFFECTIONATELY DEDICATED

PREFACE

THIS book owes its inception to the keen scientific interest of Mr. Edward D. Adams. The magnificent painting of the corona by Howard Russell Butler, which now finds an honored place in the American Museum of Natural History, New York, was originally planned that it might provide a frontispiece illustration.

Fortunately for the author, he had the hearty coöperation of many of his friends in the preparation of the book. Professor E. E. Barnard, an intimate friend for twenty-five years, furnished all of the photographs illustrating the eclipse expedition in 1901 to Sumatra. The last work undertaken by him, a few days before his lamented death, was to dictate the captions to accompany each of the photographs. Another life-long friend, Professor Edwin B. Frost, director of the Yerkes Observatory, was most generous in his assistance. As editor of the *Astrophysical Journal*, he was instrumental in providing the blocks for many of the illustrations. Professor George B. Pegram, chairman of the Adams Fellowship Committee of Columbia University, showed continued interest during the progress of the work. Dr. W. W. Campbell, director of the Lick Observatory, kindly furnished information in advance of publication regarding the Einstein problem and provided photographs of the 1922 eclipse; and this likewise was done by Dr. C. A. Chant and Dr. R. K. Young of the Canadian expedition to Australia. The director of the Lick Observatory supplied many additional illustrations from the incomparable series of photographs of the solar corona, while Professor H. Deslandres kindly sent for reproduction many photographs taken with the spectroheliograph at Meudon. Professor A. Ll. Hughes gave valuable advice and criticisms in the preparation of Chapter XIX.

The author wishes to express to these scientists his

heartfelt appreciation for their assistance so generously given, also to Mr. Alfred Noyes for permission to use extracts from his book of poems "The Torch Bearers" (F. A. Stokes), and to Mr. Leander McCormick-Goodhart for many services rendered. It is a pleasure to acknowledge services so freely given. Acknowledgment also is due the *Astrophysical Journal, Astronomical Journal, Publication of the Astronomical Society of the Pacific, Journal of the Royal Astronomical Society of Canada,* and the Lick and Lowell Observatories for the loan of half-tone blocks.

S. A. MITCHELL

MAY 10, 1923.

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INTRODUCTION

SCIENCE seems bent on increasing man's estimate of the span of time since creation began. It is now confidently believed that the human race has inhabited this terrestrial ball for at least five hundred thousand years, while Mother Earth herself must have been in existence for a thousand million years. On the assumption that mass is electrical and that all kinds of energy possess mass, we have found that the sun's heat can not be maintained for a space of time exceeding fifteen millions of millions of years, provided all its energy, including that of the atom, could be liberated. Surely such an interval is sufficiently great to satisfy even the most exacting! And yet what changes have taken place in our mode of life within the memory of man!

Today, as never before, our daily life follows its course surrounded by the wonders of science. The age of steam has brought the powerful locomotive drawing its fast and comfortable passenger train on its long journey across the continent, has constructed the gigantic ocean steamship whereby Europe is brought within four days of the shores of America, has been, indeed, the cause of the remarkable development experienced in all quarters of the globe. The internal combustion engine has largely revolutionized modes of transportation on the land, on the surface of and under the sea and in the air, so that the extravagantly fanciful writings of Jules Verne are common-place, every-day realities. The age of electricity has wrought the greatest changes of all in our daily life bringing as it has stupendous transformations in illumination vastly different from the feeble tallow dip; it has wrought the powerful motor; it has made possible the electric telegraph and telephone and the still more wonderful wireless, with the result that distance is eliminated and there is served fresh each morning

with our coffee the very latest news garnered from every quarter of the globe. Through the agency of the cinema and the wireless telephone the inhabitant of a backwoods village can gaze upon great actors, can listen to the greatest of singers and the best of symphony orchestras quite as well as if he lived in London, Paris or New York.

The bridge separating pure from applied science has been so much shortened that the gap has practically disappeared. The refined researches of the physicist or chemist today may be applied in the arts and sciences of tomorrow. Investigations in Hertzian waves in the laboratory have made the wireless telephone possible, the discovery of Mme. Curie and the remarkable work of Rutherford and others on the penetrating powers of the rays of radium have given to the cancer specialist the means of alleviating the horrors of this dread disease; X-rays are now in every-day use by the doctor, the surgeon and the dentist. And in the quiet rest of the laboratory, the chemist has experimented with his vials and test tubes and has made noxious and poisonous gases which, liberated amidst the din and roar of the battlefield, have caused the destruction of thousands of lives.

It is less than thirty years since the discovery of X-rays and radium. The marvelous researches connected with radioactivity have shown the amazing degree of refinement necessary in the work of the scientist. New forces, hitherto unknown, have been discovered, while recent researches display the amazing fact that each chemical atom takes its place in Nature as a miniature solar system. Modern investigations have revealed that one chemical element may be transformed into another, thus realizing the age-long dream of the alchemist, the transmutation of one metal into another. It has been proved that several separate series of radioactive transformations have as their end-product the metal lead, — but fortunately for the economic future of the world, the realization of the alchemist's vision of changing base lead into glittering gold seems as far distant as ever. Helium is a product of almost every radioactive transformation and it has thus become a household word with every trained physicist. And yet helium was discovered — a result of solar eclipse observations — a bare half-century ago and was isolated from pitchblende only in 1895! Within two decades the demands of the Great War brought to the attention of scientists the urgent necessity of obviating the disastrous explosions that have taken place with hydrogen-filled balloons with the consequent result that helium was produced in such large quantities that balloons were filled with this inert gas.

But amongst all the wonders of all the wonderful sciences there is no science which deals with such a gorgeous spectacle as is exhibited by the queen of the sciences, astronomy, at the moment when the earth is gradually shrouded in darkness and when around the smiling orb of day there appears the matchless crown of glory, the so-called corona. Nor can any science duplicate the wonderful precision shown by the work of the astronomer in his capacity to predict hundreds of years in advance the exact hour and minute at which an eclipse will take place and the locality on the earth's surface where such an eclipse will be visible.

The great progress of science in the last fifty years is nowhere better illustrated than in the attitude of astronomers towards observations at the time of a total eclipse of the sun. Until about the middle of the nineteenth century little interest was taken in the subject although information regarding the sun was comparatively scant. The eclipse was observed only if perchance its track happened to cross the home of the observer; the only observations of value being the exact times of contact of the limbs of the sun and moon, taken for the purpose of perfecting the lunar tables. The beautiful corona was watched with awe and admiration, a few sketches were made of its form, — but these were done with such indifferent skill that they added but little to the information available at the time. Practically no expeditions were equipped and sent away from home. How different it is in the twentieth century! In the year 1901, the United States Naval Observatory financed and sent an expedition as far from home as it could possibly go — half way round the world — and all for the purpose of making observations during a few short minutes of time. At the

recurrence of the same eclipse in 1919, the British observers in Brazil and West Africa startled the thinking world by their verification of the Einstein problem. And in September, 1922, the British astronomers on Christmas Island in the Indian Ocean had spent more than six months in preparation for reverifying this same problem only to have their work come to naught through the presence of clouds at the critical moment, while American and Canadian scientists had gone as far as the bleak shores of Northwest Australia for the same investigation.

To make such expensive and time-consuming expeditions worth-while there must be problems connected with the sun whose solution is of vital importance to the astronomer. In this book the author will endeavor to state some of these problems and the methods devised for their solution. At the same time it will be necessary to refute one of the "twice-told tales" (See *Science* during 1921) that the moon is a more important body than the sun since the moon gives us light at night when it is dark and we need its light, whereas the sun shines during the daytime when it is bright and we could possibly get along very well without it! The light that lightens the world, the heat that gives our bodies comfort, the wind that cools our heated brows and wafts the sailing ships across the ocean, the coal that warms and illuminates our homes and generates steam and electricity to carry on the world's mighty commerce, the rain that descends from heaven and waters and fertilizes the soil and causes the flow of our mighty rivers; all these and many other benefits come from the sun. Without the sun there would be no grass, no flowers, no wheat or corn or vegetable life of any kind, and without the sun there would be no animal life, no man upon the earth. If the sun were blotted out for the space of one short month, there would not be one of us left alive to tell the tale; we should all be frozen to death! It is well then that we should endeavor to learn as much as possible of the giant luminary in which are centered our light and heat and our very life, even when the quest for knowledge carries one as far from home as does eclipse work.

The life of such an observer might be likened to that of

a hunter after big game. Many months and even years are spent in quietly investigating the problems, a costly equipment is accumulated and each piece of delicate apparatus is carefully tested at home to see that it will properly perform its designated functions far afield, a long journey is often necessary, frequently of thousands of miles, by rail and sea. Arrived at the destination, instruments, cameras and spectroscopes are erected and most carefully adjusted, and after six or eight weeks of preparation in the field the eventful day approaches. Each and everyone of the party drills constantly so that the task allotted to him may be well and carefully done, so that the photographic slides may be drawn and each camera lens may be opened at the appropriate instant. Success lies in seeing that every one of a thousand possible chances of failure are obviated. At a certain hour, minute and second, the "zero-hour," operations are due to begin. But alas! there may be no "game," the eclipse may be eclipsed by clouds, and the long months of preparation may be of no avail since it will not be possible to try again on the morrow when the clouds have rolled away.

The author has traveled more than forty thousand miles to witness four total eclipses of the sun. The total time afforded him for scientific observations during these four eclipses has been a period of less than eleven minutes.

ECLIPSES OF THE SUN

CHAPTER I

EARLY HISTORICAL ECLIPSES

"In old Cathay, in far Cathay,
  Before the western world began,
They saw the moving font of day
  Eclipsed, as by a shadowy fan;
They stood upon their Chinese wall.
  They saw his fire to ashes fade,
And felt the deeper slumber fall
  On domes of pearl and towers of jade." — NOYES.

THE earliest recorded eclipse of the sun is one which happened more than four thousand years ago, an account of which is given in the ancient Chinese classic *Shu Ching*. According to the competent authority Oppolzer, this took place on October 22, 2137 B.C., about 1400 years more remote than that recorded by any other nation. This eclipse is celebrated not only for its great antiquity, but also for the dire fate of the two royal astronomers, Hsi and Ho, who instead of staying in the sober paths of science went and got beastly drunk, with the result that they were taken unawares and were unprepared to perform their customary rites of shooting arrows, beating drums, etc., for the purpose of delivering the sun from the monster that was devouring it. To show his great displeasure, not so much for failing to predict the eclipse, but on account of the intense confusion that prevailed, Chung K'ang, the fourth emperor of the Hsai dynasty, ordered that they should be punished and that their heads should be chopped off. And with this tragic warning in view, there is no record from that day to this that an astronomer has ever dared to follow in the steps of the unfortunates, Hsi and Ho, and been drunk at the time of an eclipse.

This eclipse is of such great importance that it will be well to give it more than a passing glance. The early eclipses, both of sun and of moon, have been of such great interest to astronomers and scholars that a very large number of investigations have been devoted to the determination of as exact dates as possible for these phenomena. Eclipses can take place only when the centers of sun, earth and moon are approximately in a straight line. These circumstances can be predicted with accuracy if we know with a sufficient degree of precision the motions of the earth about the sun, and of the moon about the earth. The times of eclipses thus give to the astronomer the means of accurately testing his calculations regarding the motions of both these heavenly bodies. The movements of the earth render no difficulties, but with the earth's child, the moon, the matter is entirely different. It may be truly said that the motions of the moon have given the mathematical astronomer more work and worry than those of all the balance of the gigantic universe put together. The earlier the eclipse that can be checked up with accuracy the more reliably can the motion of the moon be verified, since any accelerations in this motion depend on the square of the elapsed time. Valuable as these early eclipses are to the astronomer, they are equally important to the historian or chronicler in fixing the dates of remote antiquity. The astronomical problem has been well studied and is now regarded as a simple one. The crux of the whole question lies in the exactness and precision with which the event has been described by the author or historian.

The *Shu Ching*, or Book of Historical Documents, is a collection of public speeches and proclamations beginning with the reign of the legendary Emperor Yâo who lived in the twenty-fourth century B.C., and closing with the year B.C. 625. The book is not a historical, chronological narrative, nor indeed does such a book exist in the Chinese language. This ancient eclipse has been fully discussed by a number of eminent authorities. The most complete monograph is by Schlegel and Kühnert, Die Shu-King-Finsterniss, *Verhand. der Könin. Akad. van Wettenschappen, Letter-*

LICK-CROCKER EXPEDITION TO AUSTRALIA, 1922
32 seconds exposure with the 40-foot camera.

kunde 19, 5, 1890. Oppolzer communicated to *Monatsberichte der Kön. Preuss. Akad. der Wissens. zu Berlin*, 166, 1880. Briefer accounts may be found by S. M. Russell, *Observatory, 18*, 323, 1895; in Chambers' *The Story of Eclipses*, 65, 1900; and in the Halley Lecture delivered by Dr. J. K. Fotheringham, May 17, 1921.

In the third century B.C., Shi Hwang-Yi, a great military genius, conquered the whole of the China of those days. In 221 B.C. he proclaimed himself the " First Emperor," and he decided, on the advice of his prime minister, that every form of human progress including literature should begin with his reign. He therefore ordered the destruction of all books except those belonging to the three utilitarian branches of knowledge, agriculture, divination and medicine. To see that his orders were properly carried out, he personally examined each day a hundred pounds of books so that he might decide which were useless. Four hundred and sixty scholars were put to death for disobeying the royal commands, and others were banished for life. All copies of the *Shu Ching* seem to have perished except one incomplete copy later recovered from a receptacle where it had been walled up by a devoted scholar. The book in which the eclipse is mentioned is not included in the authentic copy. It was added later, probably to conform to a table of contents that scholars believe may have been included in the original volume, and which may possibly have been written by the great Confucius. The preface to this book is as follows:

" Hsi and Ho, sunk in wine and excess, neglected the ordering of the seasons, and allowed the days to get into confusion. The prince of Yin went to punish them. Description of this there was made, *The Punitive Expedition of Yin*."

It should be noted in the above that there is no mention of an eclipse. Tso, a scholar and commentator of the fifth century before Christ wrote concerning the lost work, *The Punitive Expedition of Yin* in the following words, " The Sun and Moon did not meet harmoniously in Fang. The blind beat their drums; the inferior officers galloped and

the common people ran about." There is further added, "That is said of the first day of this month; it was in the fourth month of Hsia, which is called the first month of summer."

In the *Annals of the Bamboo Books*, a work of the early third century before Christ, the reference to Hsi and Ho is as follows: "In the fifth year of Chung K'ang, in the autumn, in the ninth month, on the first day of the month, there was an eclipse of the Sun, when he ordered the prince of Yin to lead the imperial forces to punish Hsi and Ho."

The text does not say that the expedition was for the purpose of punishing the astronomers for failing to predict the eclipse. The scholar who restored the missing text used such flowery language that it is difficult to obtain the exact meaning, although it seems to be implied that the eclipse was the cause of the punitive expedition.

There are many uncertainties that prevent an accurate interpretation of this eclipse, chief among which may be noted: (1) The month is entirely unknown, whether it is the "first day of the last month of autumn," or, "the first day of the first month of summer." (2) The meaning of the word *Fang* is doubtful, whether it means "the order of the constellations," which seems to be the better opinion, or whether *Fang* is used in the more restricted sense as the name of a small constellation including β, δ, π and ρ Scorpii. (3) The Emperor's name is very uncertain as it is not given except in the *Bamboo Books*. Little is actually known of Chinese chronology further back than B.C. 841. We do know the names of the emperors in succession, but whether they reigned five years or fifty is unknown, and consequently all that it is possible to say about the emperor Chung K'ang is that he must have been on the throne a century or two earlier or later than the year 2000 B.C. (According to the *Encyclopaedia Britannica* the first of the kings mentioned in the Shu Ching reigned from 2357 to 2255 B.C., an interval of no less than 102 years!)

One interpretation of the above uncertainties is probably about as good as another. One date fixed by the Chinese astronomers of about the eighth century A.D., was the year

B.C. 2155. But in consequence of the fact that the eclipse of that year was invisible in China, there has arisen the well-known ditty:

> "Here lie the bones of Ho and Hi,
> Whose fate though sad was risible,
> Being hanged because they could not spy
> The eclipse which was invisible."

Taking "the last month of Autumn," and *Fang* in the restricted meaning of the word that it referred to the constellation, Oppolzer fixes the date as given above, B.C. 2137, October 22. Other authorities equally competent give other dates. The only conclusion that can be reasonably drawn is that it is not possible to identify the eclipse with any approximation to certainty. Nothing is known of the fates of the astronomers Hsi and Ho. Evidence seems to point to the fact that Chung K'ang was a weak emperor, and it is conceivably possible, as suggested by Fotheringham, that the emperor's forces may have been routed in the punitive expedition of Yin resulting in triumph for the astronomers instead of death.

Many admirers of the Chinese, not being conversant with the true facts, have pointed out this eclipse as evidence of the great learning of the Chinese and their proficiency in astronomical knowledge twenty centuries before the beginning of the Christian era. Although not wishing to dim the halo of glory that has surrounded early China, honesty compels one to draw attention to the facts. For many centuries the Chinese were unable to predict the position of the sun accurately among the stars for determining the length of the year. In fact, they seem to have relied wholly on observation from year to year to settle their calendar. No conclusions or systematic deductions were made from their observations as is shown by the fact that their calendar was continually falling into confusion.

To those who are interested in early chronological data to be fixed by this and other remote eclipses, reference should be directed also to Delambre, *Histoire de l'Astronomie Ancienne*, Paris 1817, and to Johnson's *Historical and Future Eclipses*, London, 1896.

Other Chinese Eclipses

The history of the Chinese Empire is very closely associated with the name of Confucius, the immortal sage. Confucius is the Latinized form of K'ung tsze (meaning the philosopher K'ung, this being the family name). Through his veins flowed the best blood of China. His birth has an interesting romance connected with it. His father Heih had a family of nine daughters but only one son who was unfortunately a cripple. Realizing in his old age that the K'ung name would probably become extinct with him, he went to his neighbor of the Yen clan, and told of his plight, and asked in marriage one of Yen's three daughters. The youngest of the three became the mother of Confucius, 551 or 550 B.C., Heih then being over seventy years of age. The father died in the child's third year.

In his twenty-second year Confucius began his life as a teacher, and he put into practice principles which every college professor of the twentieth century would like to follow, namely, he would accept any pupil no matter how small the fee, but as soon as lack of capacity or diligence was manifested, the youth was sent away. "When I have presented," he is reported to have said, "one corner of a subject and the pupil cannot of himself make out the other three, I do not repeat my lesson." Would that these methods of education were prevalent today! His professed disciples numbered 3000, of whom 70 or 80 were "scholars of extraordinary ability." Most of his life was spent in the province of Lu, the modern Ho-nan and Shantung.

Among the writings ascribed to Confucius are the following:

(1) A preface to the *Shu Ching*, already referred to. The preface is little more than a table of contents, and it is very doubtful if Confucius had anything to do with it.

(2) He compiled, or edited the *Shih Ching*, or Book of Poems. Originally numbering about 3000, only 311 were retained by Confucius, of which we now possess 305. It is the most ancient book of poetry in the world. The latest of the poems has the date 585 B.C.

(3) From his own hand comes the *Ch'un Ch'in*, or "Spring and Autumn," which is best known as the *Annals of Lu*, his native state. This work has been preserved almost complete. It is a brief summary of the chief events that took place in Lu during a period of 242 years from 722 to 481 B.C. It is a model for a historical document. The facts are briefly itemized according to the seasons in which they fell. As an example, in the year B.C. 612 there are twelve entries, the fifth of which was recorded, "In the autumn, in the seventh month, there was a comet which entered Pei-ton (in Ursa Major)."

In the *Annals of Lu* are records of no less than thirty-six eclipses of the sun, the first eclipse being observed February 22, 720 B.C., and the last on July 22, 495 B.C. The first of them is described as follows: "In the 58th year of the 32nd cycle in the 51st year of the Emperor King-Wang of the Chou Dynasty, the 3rd year of Yin-Kung, Prince of Lu, in the spring, the second moon, on the day called Kea-Tze, there was an eclipse of the Sun." These ancient eclipses have been carefully investigated and many papers concerning them have been published in the *Monthly Notices of the Royal Astronomical Society*. The conclusions are that it has been possible to identify no less than thirty-two of the thirty-six. Apparently four of the eclipses, those of April, 645 B.C., June, 592 B.C., September 19, 552 B.C., and June 18, 549 B.C. are in error and did not take place. The record is a history of eclipses that were actually observed to have taken place. The inference is readily drawn that the astronomers who recorded these erroneous eclipses saw some curious phenomenon around the sun; and remembering the sad fate that befell the two negligent astronomers, Hsi and Ho, and not wishing to take any chances whatever regarding the safety of their heads, they recorded the phenomenon as an eclipse.

In addition to the works from the hand of Confucius himself we are fortunately in possession of the *Tso Chuan*, a so-called commentary. This is presumably by some one with the name of Tso who took the bare entries in the work by Confucius and enlarged upon each one to such an extent

and with such remarkable genius and dramatic brilliancy that the Tso commentary reads more like a prose epic than an elaboration of a series of facts or annotations on the text of a literary work. By its means there is vividly portrayed the intrigues, the alliances, the treacheries and the jealousies of the various states which made up feudal China; we can see with the clearness almost of a photograph, assassinations, battles, heroic deeds, brilliant rescues and the torments and horrors meted out by the conquerors to their unfortunate victims. The *Annals of Lu* make the chronicles of China in the 5th, 6th and 7th centuries before the birth of Christ as full of action and as attractive as those of France and England twenty centuries later. As a matter of fact there appeared to be more of literary culture in China in these early centuries B.C. than there was in Europe a bare five hundred years ago.

The eclipse of February 22, 720 B.C. recorded in the *Annals of Lu* is not the first Chinese eclipse whose date can be accurately fixed, for fifty-six years earlier there was an eclipse of the sun preceded by an eclipse of the moon. In the *Shih Ching,* or Book of Poetry referred to above, there is an account which runs somewhat as follows: "Tenth moon, her conjunction first day, sin-mao, sun he had eclipse, also it very bad." The record ends by adding, "That moon in eclipse is a thing only common. This sun in eclipse is a thing very bad." The eclipse of the sun referred to took place on September 6, 776 B.C., the eclipse of the moon on August 21. The solar eclipse was visible only as a partial eclipse in China while that of the moon was nine-tenths total. It was during the reign of the notorius Yu-wang. It is apparent that the eclipse of the sun was regarded by the bard as a special warning to the lascivious Emperor. The evidence of this eclipse is indisputable; it fixes absolutely without controversy the first certain date in the history of China. How far before this epoch the Chinese history stretches is a matter of personal judgment and individual conjecture. As already pointed out, the records of early dates are so unreliable that one of the early kings is supposed to have reigned the impossible period of 102

years. Egypt has her pyramids and ruined temples as evidence of a much earlier civilization, but there are no such relics in China. This Chinese eclipse antedates by thirteen years the celebrated Nineveh eclipse.

Mr. John Williams, formerly Assistant Secretary of the Royal Astronomical Society, made a careful examination of the Chinese historical work called *Tung-Keen-Kang-Muh,* a record of one hundred and one volumes which contains a summary from earliest times to 1368 A.D. Information concerning these eclipses can be found in the *Monthly Notices R. A. S.* Fifty-six solar eclipses occurred between 481 B.C. and the beginning of the Christian era, and nearly one hundred additional ones before the fourth century A.D.

ECLIPSES OF BABYLON

"In Babylon, in Babylon,
They baked their tablets of the clay;
And, year by year, inscribed thereon
The dark eclipses of their day;
They saw the moving finger write
Its *Mene, Mene,* on their sun.
A mightier shadow cloaks their light,
And clay is clay in Babylon." — NOYES.

According to L. W. King, *Chronicles concerning the early Babylonian Kings, 2,* 76, 1907, it is recorded that "on the twenty-sixth day of the month Sivan in the seventh year the day was turned to night, and fire in the midst of heaven. . . ." The record seems to belong to the eleventh century B.C. Fotheringham[1] has concluded that if the day had been recorded as the twenty-eighth of the lunar month instead of the twenty-sixth, this account might then have referred to an eclipse of the sun which was visible in southern Babylonia on July 31, 1063 B.C. Unfortunately, there is no knowledge concerning the name of the king in the seventh year of whose reign the eclipse occurred. If this fact were known, the early Babylonian chronology would be fixed with fairly great certainty. It is possible to conjecture as Langdon has done that the name of this king was Nabu-shum-libur, but this name must be looked upon only as a

[1] Monthly Notices, R. A. S., *81,* 104, 1920.

suggestion. All that is known of *exact* dates in Egyptian and Babylonian chronology depends on the science of astronomy, — on the occurrence of an eclipse of the sun in 763 B.C., and on the records of the astronomer Ptolemy as given in his great work the *Almagest*.

There are no more interesting portions of the world's early history than that connected with the lands contiguous to the Persian Gulf. In Egypt, the gigantic pyramids, the construction of which is justly regarded as one of the seven wonders of the world, and the ancient temples point to a civilization that was in a high state of development five thousand years ago. Across the narrow Red Sea, more interesting even than the land of the Pharaohs, is the country of the Holy Scriptures where lived Adam and Noah, the great King David, the holy prophets and the immortal Jesus Christ. Up to the middle of the nineteenth century little was known of ancient Babylonia and Assyria other than the account given in the Bible. The country which is nearly enclosed by the two great rivers the Tigris and Euphrates from Bagdad to the Persian Gulf is bounded on the north by Mesopotamia, on the east by the plain of Elam, on the south by the Persian Gulf and on the west by the Arabian Desert. To the north, in Mesopotamia, the country is more or less mountainous, while to the south the terrain is flat and marshy. In ancient times the plain was covered with a complicated network of canals. The remarkable fertility of the soil brought such great prosperity to these peoples that they aspired to be the masters of the world. According to Herodotus (i, 193), wheat commonly returned two hundred-fold to the sower, while Pliny (*N. H.* xviii, 17) states that it was cut twice each year. The native historian Berossus remarked that wheat, barley, palms, apples and many kinds of shelled fruit grew wild. The country was studded thickly with towns. But alas, — the neglect of the canals has changed the face of the land so completely that the fertility that was once the wonder of the ancient world has departed, and in its place there is nothing but a barren and desolate waste, part of the year the land being a series of swamps and marshes.

The ancient city of Babylon was on the east bank of the Euphrates about seventy miles south of Bagdad. The plain of Babylonia was called Edin, the "Eden" of Genesis ii. The chief city of Assyria, Assud, was on the west side of the Tigris, while the three other great cities of Nineveh, Calah, and Arbela were on the eastern bank of the Tigris.

The excavations at Nineveh by Botta and Layard opened up a new world. Layard after indescribable difficulties laid bare the palace of Sennacherib (705–680 B.C.) and that of Assurbanipal (668–626 B.C.), and in the palace of the latter was found a great library of tablets which finally numbered no less than thirty thousand. These objects when not too massive were transported to the Museum of the Louvre or to the British Museum. The success of these discoveries stirred scholars throughout the world, and the different nations vied with each other in the prosecution of the interesting search. The British and French continued their investigations, and in 1886 German archaeologists began their work. Since 1888 expeditions have been organized by the University of Pennsylvania and since 1903 by the University of Chicago.

The language in which the ancient history is preserved is the so-called Babylonian-Assyrian wedge-writing, the cuneiform language of signs. No such thing as an alphabet was known. As the $ sign means much to the American, while to the resident of the British Isles the synonym of money is conveyed by a different symbol, £, so these primitive people expressed themselves in their tablets entirely by signs. A wedge was used to make an impression in clay, and the different combinations served to express a variety of ideas. The decipherment of these tablets was a difficult task. The most important progress was made through the work of an Englishman, Henry C. Rawlinson, who observed at Behistun a rock stretching up almost 1700 feet above the plain, and at a point about 350 feet above its base there was a large space carefully smoothed off. On this was found a mass of inscriptions distributed in columns of various lengths. After long years of work he succeeded in transcribing the whole of the record. Careful study and long

and arduous toil revealed the fact that the writing was in three different languages, old Persian, Elamite and the Babylonian. The decipherment was excessively difficult due to the enormous number of signs employed. For simple names there were about 600 independent and distinct signs made by combinations of wedges numbering anywhere from two to thirty. But two to six of these signs might be compounded to express more complicated ideas, with the result that there are something like 20,000 different signs known to students of Assyriology. The number of inscriptions so far found number about one hundred and fifty thousand.

The earliest mention of Babylon appears to be about 3800 B.C. The first great king was Sargon of Akkad who lived about 2750 B.C. Even greater was Khammurabi the Amorite who flourished about 2100 B.C. Concerning this latter monarch, who lived over four thousand years ago, we have positive information in a group of fifty-five of his letters edited by L. W. King, and in a monument giving a code of splendid laws. From his letters we learn that the Babylonians kept their record of time entirely by the moon, a new month beginning with each new moon. Twelve lunar months made up the year. Since the synodic month is of twenty-nine and a half days in length, it became necessary to add in the reckoning of the year a thirteenth month from time to time in order that the calendar should not get astray.

This method of measuring the length of the year, which is both inaccurate and inconvenient, was followed by the Hebrews and the Persians. Even in the enlightened age of the twentieth century the Jewish and Mohammedan calendars are still based on the old custom. An intercalary month being inserted in the reign of Khammurabi, he accordingly sent out a circular letter to his governors advising them that the delinquent tax gatherers should not take advantage of the change in the calendar and that the taxes must be paid without delay. Schools flourished even at this remote period, and tablets have been found which evidently were exercises of the children as they struggled to learn the language of signs. In fact a Babylonian proverb

has been unearthed which reads, "He who shall excel in tablet-writing shall shine like the sun."

The kingdom of Assyria begins about 3000 B.C. Assyria was a warlike nation, and lived by the sword. In the eighth century B.C., their conquests had been pushed as far westward as Damascus and to the Hebrew city of Samaria. While besieging this latter city, the king was deposed and a usurper called Sargon took the throne. Under him and his son Sennacherib, Assyria was at the zenith of its military power. Campaigns were carried out in Ionia and Greece and also southward as far as Egypt, which became tributary to Assyria. In Nineveh, Sennacherib constructed the largest and most magnificent palace the world had seen up to this time. In 689 B.C. he conquered the city of Babylon, and he caused this holy city to be completely destroyed and all of its buildings razed to the ground. After many years Babylon under Nabopolassar, revolted from the Assyrian yoke and under his son Nebuchadrezzar — the Nebuchadnezzar of the Bible — construction on a great scale was carried out, and Babylon was rebuilt and became the wonder city of the ancient world. According to Herodotus, the walls were no less than 56 miles in circumference, the walls being 335 feet high and 85 feet wide. Each city had its great temple and its own god, the god of Babylon being Bel-Merodach. In the temple stood an enormous image of the god forty feet high, together with a table, a mercy seat and an altar, all constructed of gold. In this reign (604–561 B.C.), the rebuilt Babylon was at the height of her glory and the summit of Chaldean civilization had been reached.

This glimpse of the history of these early peoples of such great interest to all Christian countries is for the purpose of giving a setting for ascertaining what they had accomplished in art, literature and science — particularly in the science of astronomy. Assyria differed much from Babylonia. The former state was an armed camp and held sway by the sword, probably even in those early times believing that might is right. On the other hand, the Babylonians were peace-loving people, a land of merchants and farmers, and

withal deeply religious. Consequently, Assyria had little culture of its own and the little it did possess was borrowed or acquired from Babylonia.

One of the grandest epics of ancient Babylonia was the description of Creation which is mentioned here on account of its astronomical significance and also that it may be compared with the Biblical description. In the first book an account is given of the creation of the world out of the primeval deep and the birth of the gods of light. Then comes the story of the struggle between the gods of light and the powers of darkness, and the final victory of Merodach, who clove the dragon of chaos, Tiamat, asunder, forming the heaven out of one half of her body and the earth out of the other. Merodach next arranged the stars in order, along with the sun and moon, and gave them laws which they were never to transgress. After this the plants and animals were created, and finally man. Merodach here takes the place of Ea, who appears as the creator in the older legends, and is said to have fashioned man out of clay.

Thus from very earliest times, the religion of the Babylonians was inspired by the belief that the heavenly bodies were subject to law and order and that they ruled the destinies of man. It was evident even to the simple mind of the primitive man that the sun was the cause of all life on the earth, and it was a natural conclusion that the ever-changing aspect of the sun, moon, planets and stars should be connected with the constant mutations in the lives of the individuals of the race. Hence their gods and goddesses were identified with the heavenly bodies. The priests became astrologers. To be able to read the signs of the heavens seemed to be synonymous with understanding the happenings on earth, and consequently if this knowledge were to be utilized to predict what would take place in the future it was necessary to follow with the minutest care the various motions of the sun, moon, planets and stars, — and hence the priests became astronomers. These religious beliefs caused a systematic study of the heavenly bodies; and as a result astronomy, the first and parent of all of the sciences, had its birth.

Solar Corona, September 21, 1922
Exposure 2 seconds. Lick Observatory Expedition to Australia.

The movements of the sun and moon were symbols of law and order, and accordingly they were worshipped as gods. The motions of the planets, though more difficult to understand, seemed also the subject of order and not of caprice, and so likewise they were worshipped. Jupiter was the abode of the Babylonian god Mardok, and Venus was the home of the goddess of love, Ishtar. Saturn was identified with Ninib, Mercury with Nebo, and Mars with Nergal. In order to understand the manner in which the gods of the sun, moon and planets influenced the lives of men, it was necessary for the Babylonian priests to observe the position of these bodies, not only with respect to each other, but also with respect to the more prominent and easily recognizable fixed stars. In the case of the moon it was very necessary to note the time at which the new moon became visible as a crescent, its position in the heavens, and the angle made with the horizon by the line through the horns. (Even at the present supposedly enlightened age of the twentieth century A.D., we still hear of the "wet" moon, and the "dry" moon.) The changes of the moon were followed with meticulous care since each change afforded the opportunity of interpreting some phase of human activity. And through forty centuries of the world's history some of these superstitions have survived in the popular belief that a change in the moon means a change in the weather, or that certain crops should be planted "in the dark of the moon." These observations of the heavenly bodies being thus gradually accumulated must have reached a mass of considerable proportion. For his interpretation of these observations the astrologer rested on written records or on the recollection of what had happened under similar circumstances in the past, but sometimes merely on the vagueness of association of ideas.

The motion of the sun and moon among the stars near the ecliptic being carefully observed, it was but natural that the twelve full moons of the year should suggest the division of the circle of the year into twelve parts. We thus owe to the Babylonians the constitution and nomenclature of the twelve signs of the zodiac. Ages before Assurbanipal's

great library of tablets was constructed, the eighth month was known as "the month of the star of the Scorpion," the tenth as "the star of the Goat," while the twelfth was the month of "the star of the Fish of Ea." The convenience of the duodecimal system was thus early recognized. Each day was divided into twelve "double hours." The *ner* of 600, the *sar* of 3600 was formed from the *soss*, or unit of 60. The circle was divided into 360°, or six times sixty, with further divisions by 60 into minutes and seconds of arc, the hours being likewise divided into minutes and seconds of time. According to Miss A. M. Clerke, "In the Chaldean signs of the zodiac, fragments of several distinct strata of thought appear to be subdivided. From one point of view they shadow out the great epic of the destinies of the human race; again the universal solar myth claims a share in them; hoary traditions were brought into *ex post facto* connection with them; or they served to commemorate simple meteorological and astronomical facts." Astronomy was thus of very old standing in Babylonia. The principal astronomical work, called the *Illumination of Bêl* was compiled for the library of Sargon of Akkad; it was inscribed on 70 tablets, and apparently went through numerous editions, one of the tablets being in the British Museum. It treats, among other things, on observations of comets, the pole star, the conjunction of sun and moon, and the motions of Venus and Mars.

However, since the study of orderly motions of the heavenly bodies was primarily for the purpose of forecasting human events, it is not surprising to learn from modern researches that the early astronomical knowledge was very crude, with very little perfection in the observations. It is true that as early as the days of Khammurabi (2100 B.C.) there were combinations of prominent groups of stars into outlines of animals and figures, yet there is no evidence that prior to 700 B.C. more than a small number of the constellations of the zodiac had found their place in the sky.

The Babylonians had tables of squares and cubes calculated from 1 to 60, they measured time by the sun-dial and by water clocks, were familiar with lever and pulley, and

even possessed a lens turned on a lathe, such a lens having been discovered by Layard. Such proficiency on the part of this early people would lead one to expect that though their observations may have been crude they had nevertheless perfected systems of moon calculation and planetary tables of a high order of excellence. The discovery of the Saros of 223 lunations, so useful and important in the predicting of eclipses, has been attributed to the Chaldeans. They seem also to have been aware that Venus returns in almost exactly eight years to the same point in the sky and to have established similar relations of 46 years for Mercury, 59 for Saturn, 79 for Mars and 83 for Jupiter. They were thus able to fix in advance the positions of the heavenly bodies, of such great importance in astrological lore. In fact it is generally thought that Hipparchus, the first great astronomer of the world, acquired much of his information from the Chaldeans, though unquestionably he verified all of their findings. The Babylonian sage Berossus founded a school about 640 B.C. in the island of Cos, and it is not impossible that Thales of Miletus was one of his pupils.

In spite of the unbounded admiration which one must feel for the development of astronomy under the Chaldeans it seems much more plausible to believe that the greatest work of the Chaldeans was accomplished in the later years of their history, this taking place even after the fall of Babylon in 539 B.C., and in fact after the Greeks had invaded the valley of the Euphrates. This matter, and particularly their acquaintance with the Saros, will be further discussed in dealing with the famous eclipse of Thales.

The study of astrology thus securing a firm foundation under the Babylonians, it spread from them, directly or indirectly, to all quarters of the globe. It came to Greece about the middle of the fourth century B.C., and reached Rome before the opening of the Christian era. In India and China both astronomy and astrology were acquired from the Greeks, and are largely reflections of Greek theories and speculations. By the introduction of Greek culture into Egypt, astronomy and astrology were both cultivated in the land of the ancient Pharaohs during the Greek and

Roman periods. The Arabs developed astrology and also astronomy, many of the names of the brighter stars being Arabic. In Europe as late as the 14th and 15th centuries, astrologers had important positions at the royal courts and were consulted on all matters of great moment to the nation. With the revival of learning, and particularly after the development of the Copernican system which showed that the earth was but one of the planets, astrology became more and more pushed into the background, though as late as the 17th century horoscopes were cast by the great astronomer Kepler. Even in the United States of America and in England there are still many thousands of people who believe in the flat earth, and who have great confidence in the efficacy of horoscopes correctly to forecast the future. Traces of the Babylonian astrology are still found in our every-day language, for we still have such phrases as "I thank my stars," he was "born under a lucky star," or an "ill-starred undertaking."

As already stated, the Babylonians had a calendar of twelve lunar months, and a seven-day week, the seventh day being a day of rest. The early Babylonians reckoned events from some great catastrophe, such as in our day, Chicago and its great fire, but later in their history they counted time by the years of the reigning king. There were several early dynasties, but the succession of rulers is fairly certain. In Assyria, on the contrary, a plan unique among the early peoples was followed in naming the year after officers, called eponyms, whose term extended for one year only. This "Eponym Canon," as it is called, began with the year 911 B.C. In the *Almagest* of Ptolemy there is a list of Babylonian, Assyrian and Persian kings who ruled in Babylon together with the years each of them reigned beginning with the accession of Nabonassar in 747 B.C., to the conquest of Babylon in 331 B.C. by Alexander the Great. This Ptolemaic Canon is confirmed by other Babylonian chronicles and also by the Assyrian Eponym Lists.

These Assyrian tablets record three eclipses of the sun. The first, interpreted by Rawlinson in 1867, is referred to as follows: "In the Eponymy of Burgasole, Governor of

Gozan, a revolt in Assur took place in the month Sivar, and the sun was eclipsed." To call attention to the importance of the event the ancient scribe drew a line across the tablet. This eclipse has been carefully investigated by a number of astronomers, by Ginzel, Airy, Hind and others, and the general conclusion is that Nineveh, where lived the Assyrian scribe, was just outside the path of totality, and that the greatest obscuration was about 9:47 in the morning of June 15, 763 B.C. The second eclipse mentioned in the Assyrian records took place in the reign of Esar-haddon, the son and successor of Sennacherib. This eclipse was partial in Assyria, but annular farther to the east, and the date was May 27, 669 B.C. The record of the third is a little uncertain, but it is probably the eclipse of June 27, 661 B.C., during the reign of Assurbanipal.

These are not the only eclipses observed by the Chaldeans, for in the *Almagest* of Ptolemy is a record of three eclipses of the moon observed in Babylon. The first of the three was a total eclipse on March 19, 721 B.C., while the other eclipses, partial only, were observed the following year, on March 8, and September 1. As has been stated above, Ptolemy gave a list of the kings who reigned in Babylonia. These eclipses, of sun and moon, fix the dates of Eastern chronology with great exactness, the earliest date in the world's history to be thus accurately determined being the year 911 B.C. in Assyrian chronology. Earlier dates are known with increasing uncertainty. The various estimates of historians for the beginning of the first Egyptian dynasty differ as much as two thousand years!

As a result of the Babylonian eclipses, it has been necessary to alter the chronology of the Bible by lowering the dates to the extent of twenty-five years. This will be referred to later in connection with passages from the Holy Scriptures in Amos and Isaiah.

Egyptian Astronomy

In the neighboring country of Egypt excellent opportunity must have been afforded for a study of astronomy on ac-

count of the clear skies of the East and from the intercourse which must certainly have taken place between the Egyptians and the Chaldeans of Asia Minor. Egyptian records accordingly have been carefully scrutinized to find what traces there are of early astronomical knowledge in the land of the Nile. And since a study of eclipses must concern itself with the beginnings of astronomy, a brief glance will be given here to early history in Egypt.

The early Chaldean monuments are probably of an earlier date than those of Egypt, but the former are almost formless piles of sundried brick, while the tombs and pyramids of the early Egyptian dynasties are many of them in excellent preservation. The history of Egypt is generally divided into five periods:[1] (1) The Ancient Empire, 3400–2160 B.C., comprising ten dynasties of kings; (2) the Middle Empire, with Thebes as capital, two dynasties; (3) the second Thebic, or New Empire (1588–1150 B.C.), comprising dynasties XVII–XX, separated from the Middle Empire by the Shepherd Kings of Arabia; (4) the Decadence period of six dynasties, 1150–324 B.C., which includes the Persian conquest in 525 B.C.; and (5) the Ptolemaic and Roman period, 324 B.C.–300 A.D.

Little is known of exact dates before the Conquest by Alexander although repeated attempts have been made to determine them. The list of the succession of the Egyptian kings is known with certainty, but the chronology is uncertain for the following reasons: (1) The lengths of the individual reigns are not known with precision, since the record seldom reached to the end of the reign, and did not allow for co-regencies. (2) Calculations on the *probable* length of a period leads to no trustworthy information. (3) Comparisons with other records, particularly with those of Babylonia and Assyria, give the most valuable knowledge. But the dates before 911 B.C. are not known accurately even in Assyrian chronology, and it is therefore not surprising that the date of the beginning of the XIXth dynasty should be estimated by competent authorities anywhere from 1490 B.C. to 1315 B.C. (4) Of most interest to us here is the

[1] Hamlin, *Encyclopedia Americana*, 10, 12.

astronomical information. The Egyptian number system was decimal, each power of 10 up to 100,000 being represented by a different figure, on much the same principle as the Roman numerals. The day was divided into two periods, each of twelve hours, the beginning of the day being the time of sunrise. The year was divided into twelve months, each of thirty days, or a year of 360 days. As early as the Vth dynasty, the premature arrival of the seasons was noted, and as a consequence five complementary days were added making a year of 365 days. The extra days were counted either at the beginning or at the end of the year. The year was divided into three seasons, each month into three weeks, each of ten days. Since the season of agricultural growth depended more on the inundation by the Nile than on the motion of the sun, the first of the year was reckoned as the beginning of the rise of the waters of the river. As this took place with fair regularity, the Egyptians were thus furnished with a useful starting-point for their annual counting of time. It was noticed that the brilliant dog-star, Sirius, or Sothis, rose with the sun about this time (July 19), and as this star is so brilliant, refined astronomical measurements were not necessary in order to observe it. But the tropical year, the year of the seasons, is approximately a quarter of a day more than 365 days. (The tropical year is now known to be equal to 365.2422 mean solar days.) Hence the Egyptian calendar got astray one month every 121 years, or one year every 1461 years. This period, during which the New Year's day of the Egyptians traveled all round the calendar, was known to Greek and Roman writers in the first century B.C. Would that Julius Caesar when revising the Calendar — the Julian being the basis of the Gregorian, or modern calendar — had followed the simplicity of the Egyptian calendar, at least in keeping each month of a uniform number of days, and would that pride and jealously had not robbed poor February of two days! The modern calendar is very awkward and inconvenient, and there have been many attempts suggested for the purpose of revising it. Most of the modern revisions proposed call for an extra day in the year, or two extra days in leap years,

which days are not to be included in the reckoning of any week or any month. Attention should be called to the fact that the five extra days of the Egyptian year — recorded as early as the Vth dynasty — were regarded as so peculiarly unlucky that there is not a single instance, among the many thousands of inscriptions brought to light, of any contract being entered into on any one of the five complementary days, nor has any event of importance ever been recorded as taking place on one of these unlucky days.

The brilliant skies of Egypt favored the development of observations. It is generally believed that the Egyptians observed the motions of the heavenly bodies for the purpose of fixing the dates of their religious festivals. These times were probably noted by observing the times at which certain of the brighter stars arose at dawn just before the sun. For accomplishing this object no instruments were necessary.

They also determined the hours of the night by observing the meridian passage of certain stars. What is thought to be the oldest astronomical instrument in the world, which is now in the Berlin Museum, was probably utilized for this purpose. It consisted of a handle supporting a plumb bob and a reed which served as a sighting vane. By means of this and with the help of the ancient Egyptian *horoscopus*, or clock, the meridian could be laid out and time determined by observation. There have been preserved the titles of several temple books, which books apparently recorded the movements of the sun, moon and stars, but unfortunately, not a single one of these records themselves have survived. The Egyptians were of an intensely practical turn of mind, and they had little desire to acquire knowledge for the sake of the knowledge itself. If the information could be utilized for any practical use it was carefully cherished and preserved, or if it could assist in their religious speculations it was then regarded of great value. If we are to judge of the accomplishments of the Egyptians by the written documents alone, we must assume that they knew little and cared less for any branch of science. But then, there are the pyramids, and the great temples such as Karnak! Surely the architects and engineers who constructed such colossal

monuments must have possessed knowledge of surveying vastly greater than is shown by any written record. The construction of the Great Pyramid apparently took place less than a century and a half after the elevation of the earliest piece of stone masonry known. Since these pyramids could have been erected only by means of great mechanical power, we are forced to the conclusion that the progress in the control of such power was greater at the thirtieth century B.C. than at any other age of the world's history except the present. The pyramid was placed four square to the points of the compass, and leading to the sepulchral tomb there was a passage at an angle of 26° to the horizon, which has been thought furnished a corridor for observing the star which was then the pole star, α Draconis. With this assumption, an estimation has been made of the possible age of the pyramids. According to C. Piazzi Smyth, the passage in the pyramid facing the south was used for the observation of the meridian passage of the stars and planets, and it is even possible that the moon and sun were similarly observed. According to Proctor, if the Egyptians had utilized an opaque screen with a small round hole in it at the southern end of this gallery they could even have observed sun-spots!

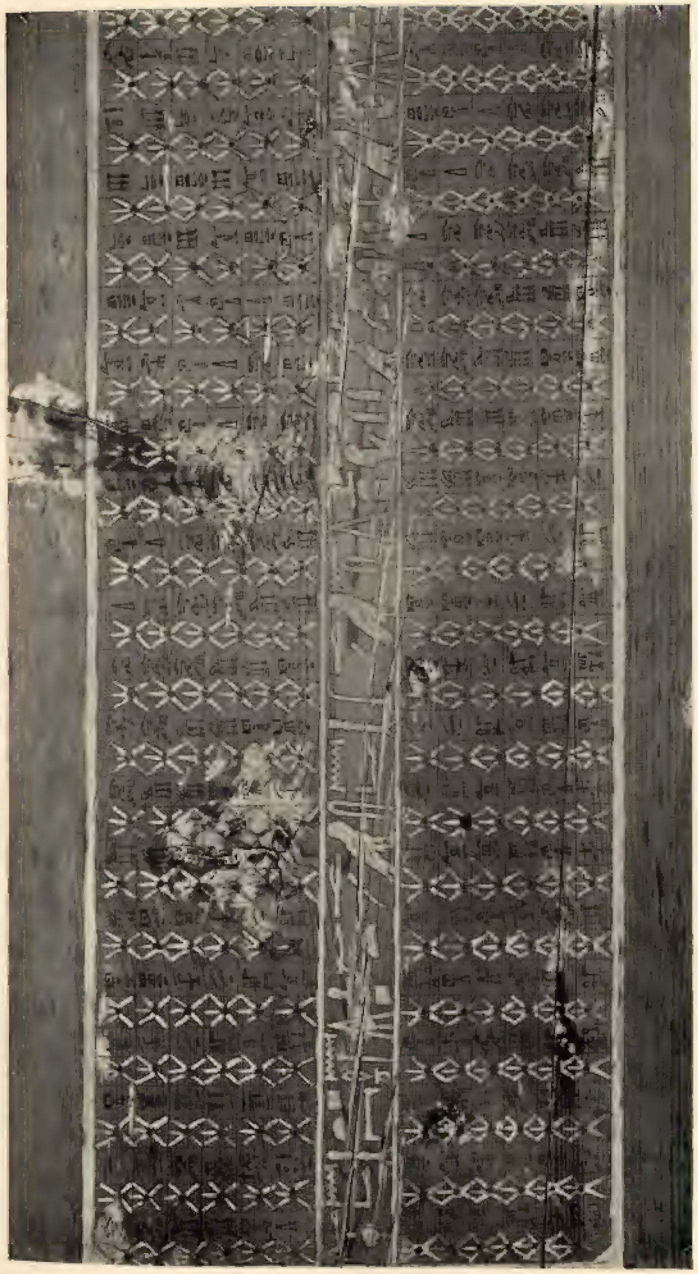
In early paintings appear the sun, moon and the five known planets, and also thirty-six *dekans*, three being assigned to each twelfth part of the circle of the ecliptic. The constellations to which were assigned animal or other forms, such as the Lion and the Bull appear to have been known. The signs of the zodiac were not acquired from the Chaldeans until fairly late in Egyptian history, for there is no record of them until after the Ptolemaic period.

According to E. W. Maunder, the symbol of the sun-god, so frequently found on Egyptian monuments, is sufficient evidence to prove that total eclipses of the sun were observed in Egypt. The general design of this symbol is a circle with striated wings to right and to left, and with a lesser extension in the downward direction, but with nothing above the circle. As pointed out by Maunder, the extensions to right and left call to mind and resemble the form of the solar corona when the eclipse, oc-

curring at sun-spot minimum, has the equatorial wings. This explanation is indeed plausible, and it is not impossible that it represents the truth. To use the coronal form for the symbol of the sun would have necessitated that the corona had been frequently observed by the Egyptians, and at more than one age. Such symbols could be adopted by a people only after slow awakening and continued observation. Consequently, if eclipses had been so frequently observed it would be rational to expect that records of some of them would have been preserved. Considering the frequency with which eclipses were observed in Babylon, it is surprising in the highest degree to find not a single reference anywhere in Egyptian antiquity to an eclipse, either of the sun or of the moon. We are therefore forced to the conclusion that the Egyptians had little part in the development of the science of astronomy.

The New Empire beginning with the XVIIIth dynasty marks the golden period of Egyptian life. This was the age of conquest with an empire stretching from the Euphrates to the fourth cataract of the Nile. Egypt had become a great military empire whose world power lasted from the early sixteenth to the twelfth century B.C., or over four hundred years. The capital was the once vast city of Thebes constructed on both sides of the river Nile, the first great monumental city built by man. On the east side of the river is the temple of Karnak which is nearly a quarter of a mile long and was nearly two thousand years in the course of construction. The obelisk of Queen Hatshepsut, the first great woman queen of history, is still standing. This is about one hundred feet high and weighs 350 tons. The first of the world's great generals was Thutmose III, who ruled for fifty years beginning about 1500 B.C., and on the walls at Karnak are inscribed the stories of his great exploits.

The recent discovery of the tomb of Tut-ankh-Amen has brought into sudden prominence that portion of Egyptian history immediately following the reign of Thutmose III. While little light so far has been thrown on the actual historical facts of the lives of Tut-ankh-Amen and his im-



An Ancient Egyptian Calendar

mediate predecessors, the incomparable beauty of the objects of art found within the tomb bids fair to revolutionize the history of Egyptian art and literature. It is to the influence of the religious upheaval brought about by Khu-n-aten, the successor of Thutmose III, and reputed father-in-law of Tut-ankh-Amen, that the revolution in artistic and literary expression is due. This monarch, known as the "heretic king," physically a weakling, mentally a poet and dreamer, revolted from the polytheistic religion of his forefathers and founded a new faith which deified the sun as the giver of all light and life. This worship, with Aten the sun as its visible symbol, had many points in common with Christianity and has been regarded as the most beautiful of the ancient religions. In his enthusiasm for the new faith, however, Khu-n-aten allowed the material needs of his empire to go unheeded to such an extent that at his death the confusion and distress throughout Egypt was so great that his successor was forced to give way to the strong political power of the priests of the old religion, and Amen once more became the chief Egyptian god. It was in the shadowy period between Khu-n-aten and Rameses I that Tut-ankh-Amen's brief reign occurred.

The XIXth dynasty began with Rameses I, whose reign, according to Breasted, commenced about 1315 B.C. This king reigned only two years, but he had planned and had started construction on the great colonnaded hall at Karnak, the greatest of such edifices ever constructed by man. It is 338 feet long and 170 feet wide. There are one hundred and thirty-six columns in sixteen rows, those in the nave being higher than the rest. Rameses shared his throne with his son Seti I for one year, and Seti continued the gigantic plans of his father. In addition he built a splendid temple at Abydos, and a magnificent tomb in the Valley of the Tombs of the Kings. This galleried tomb is the very finest of its kind. The decorations are wonderfully charming, full of life and color though perhaps lacking some of the strength and character of earlier art. The outlines are forceful, the postures natural and the coloring beautiful. Egyptian art

had reached the pinnacle. The Metropolitan Museum of Art of New York has been conducting operations at this magnificent tomb of Seti I. The photographs of the tomb examined with care give glimpses of the glories of the tomb and show some of the decorations which include the Lion surrounded by stars and the Bull. A careful scrutiny of photographs of this and other tombs appears to show that the stars connected with the Lion and the Bull in no way refer to the well-known zodiacal constellations of Leo and Taurus. In spite of many writings to the contrary, it appears tolerably certain that the Egyptians, throughout the long years of their interesting history, contributed but little to the *science* of astronomy.

CHAPTER II

BIBLICAL AND CLASSICAL ECLIPSES

IT IS safe to say that there is certainly one allusion in the Holy Scriptures to a solar eclipse, with one or two others possible. In Amos viii, 9, appear the words, " I will cause the sun to go down at noon, and I will darken the Earth in the clear day." The language is so unmistakable and gives such a precise description of an eclipse of the sun that commentators have generally agreed that such a phenomenon must have taken place. This and other Scriptural references have been so fully and so carefully investigated by Chambers in *The Story of Eclipses,* and by Johnson, *Eclipses, Past and Future,* that a brief reference only will be given here.

The date set down in the margin of certain Bibles opposite this passage in Amos is 787 B.C. Eclipses were visible in the neighborhood of Samaria in the years 791 B.C., 771 B.C., 770 B.C. and 763 B.C. This last mentioned is the eclipse of Nineveh already described, an eclipse which was visible also in Samaria. There seems no doubt whatever that this is the eclipse predicted by Amos. It therefore becomes necessary to lower by twenty-four years the date given in Amos; and if this is done there is a ready explanation of the story in the life of King Hezekiah, as given in II Kings xx, 11. The Old Testament thus reads: " And Isaiah the prophet cried unto the Lord: and he brought the shadow ten degrees backward, by which it had gone down in the dial of Ahaz." Ahaz was the father of Hezekiah, and the " dial " was probably a sun-dial similar in construction to the ancient sun-dials of masonry still existing at Benares and Delhi in India.

The Biblical peoples at this period of their history were divided into two. In the North, the land was rich and fer-

tile and great prosperity and wealth abounded. The people lived in large towns, they dressed and lived extravagantly. Moreover these people of Israel had adopted the gods of the Canaanites, each town in fact having its own god, or " baal." To the South, the land was poor, encroaching as it did on the desert, and the people of Judah had to struggle for their existence. The only large town was Jerusalem. The Jews were still faithful to the Hebrew God, Jehovah. The shepherd Amos being a devout follower of Jehovah made a journey to Israel, and thundered his denunciations against their many gods, and against their gaudy clothes, their licentiousness and harsh treatment of the poor.

About this time the Hebrews were beginning to learn to write, and they were abandoning the clay tablet and the cuneiform inscription of the Assyrians and Babylonians. They wrote on papyrus and with pen and ink, which method of writing they had acquired from their former masters, the Egyptians. However, they borrowed the first alphabet the world had developed, that of Phoenicia. The papyrus rolls written by Amos and other historians have descended to us as the Hebrew Scriptures. On account of the evil lives of the people of Israel, Amos predicted their destruction. Damascus was taken by the powerful Assyrians in 732 B.C., and thus being unprotected on the north, Samaria, the capital of the kingdom of Israel, was captured in 722 B.C., the Israelites being taken away captive and their nation detroyed.

Shortly before 700 B.C. arose the great prophet Isaiah. In one great oration after another he exhorted the people of Jerusalem to believe in their God, Jehovah, and not be dismayed for He would deliver them from the hosts of the powerful Assyrian, Sennacherib, who was then threatening to batter down the city. The king of Jerusalem, Hezekiah, was sick unto death, and the same tragic fate as had befallen Damascus and Samaria seemed to be awaiting the people of Jerusalem. In answer to a prayer of Hezekiah for recovery the prophet was sent to him with this message: " Thus saith the Lord, the God of David thy Father, I have heard thy prayer, I have seen thy tears: behold I will add

unto thy days fifteen years . . . and I will defend this city, and this shall be a sign unto thee from the Lord, that the Lord will do this thing that He hath spoken. Behold, I will bring again the shadow of the Sun, which is gone down in the sun-dial of Ahaz ten degrees backward, by which degrees it had gone down." (Isaiah xxxviii, 5–8.)

There was a large partial eclipse of the sun visible in Jerusalem on January 11, 689 B.C. If we accept the correction of twenty-four years derived from the record of the eclipse of Nineveh, then according to Chambers (*loc. cit.*), this eclipse of Jerusalem will completely satisfy the Biblical narrative at all points. History tells that a pestilence from the marshes of the Nile caused great havoc in the army of Sennacherib, and thus was Jerusalem miraculously spared. See also in this connection, II Kings, xix, 32–37. About a century later the Hebrews rejoiced over the destruction of Nineveh in 606 B.C. But unfortunately, the days of Jerusalem were numbered. The Chaldeans followed Assyria as masters of Palestine, Jerusalem was destroyed in 586 B.C. under Nebuchadnezzar, and the people were carried away into exile in Babylon.

The dates herewith given in Babylonian and Assyrian history admit of no uncertainty since they are determined by eclipses. As a consequence, the dates appearing in the Bible must be altered to fit those of verified history. It would be interesting to follow the history of the Hebrews through the lives of Jeremiah and other prophets — but space forbids. The reader is referred to Breasted, *Ancient Times, a History of the Early World*, and also to many other books on this period of history which is of the greatest of interest to all Christian peoples.

Eclipses of Classical Literature

It will be possible to give an account here of but a few of the eclipses referred to in the Classics, and we shall begin with Homer. On the day of the slaughter of the suitors, there is a passage in the *Odyssey* (v. 351–357), which probably refers to an eclipse of the sun. The lines run:

"Ah, wretched men, what evil is this that you suffer? Shrouded in night are your heads and your faces and your knees beneath you; kindled is the sound of wailing, bathed in tears are your cheeks, and sprinkled with blood are the walls and the fair rafters. And full of ghosts is the porch and full the court, of ghosts that hasten down to Erebus beneath the darkness, and the Sun has perished out of heaven, and an evil mist hovers over all."

According to Fotheringham (*loc. cit.*), the words, "The Sun has perished out of heaven," must refer to a total eclipse, and in fact most commentators, including Plutarch and Eustathius, agree in this interpretation. Apparently, the eclipse was contained in the legend as it descended to Homer, — though naturally it is impossible to fix the exact date of the eclipse.

The next eclipse is one referred to by the Greek poet Archilochus, a portion only of whose work has come down to us. The lines are: "Zeus, the father of the Olympic Gods, turned mid-day into night, hiding the light of the dazzling Sun; and sore fear came upon men." According to the investigations of Oppolzer and Millosevich, the poet must have witnessed the eclipse of April 6, 648 B.C., the eclipse being total about 10 A.M. at Thasos and in the northern part of the Aegean Sea. We know that the poet spent part of his time at Thasos, and if his statement actually gives the description of an eclipse, it thus furnishes the earliest date in Grecian chronology to be fixed with certainty. The early accepted dates must accordingly be reduced by fifty years, but no surprise need be felt as they were known only with great uncertainty.

Eclipse of Thales

The most celebrated eclipse of all history is that connected with the name of Thales of Miletus who lived from 640 to 546 B.C. He was the founder of Greek astronomy, geometry and philosophy. He was regarded by the Greeks with great veneration, and he was the chief of the seven "wise men," a reputation which rested not only on his

scientific eminence but also on his political sagacity. According to the historian Herodotus (i, 74), the reference to the eclipse is as follows: "There was war between the Lydians and the Medes for five years, each won many victories from the other, and once they fought a battle by night. They were still warring with equal success, when it chanced, at an encounter which happened in the sixth year, that during the battle the day was turned into night. Thales of Miletus had foretold this loss of daylight to the Ionians, fixing it within the year in which the change did indeed happen. So when the Lydians and Medes saw the day turned to night they ceased from fighting, and both were the more zealous to make peace." The truce concluded was cemented by a double marriage, "for," adds the historian, "without some such strong bond, there is little of security to be found in men's covenants." The same eclipse is referred to by both Pliny and Cicero.

The narrative by Herodotus contains two statements, that the eclipse was total (a "night battle"), and that the eclipse was predicted by Thales. It is in regard to the second fact that the controversy has arisen among astronomers. Various dates for the eclipse have been assigned, from 625 B.C. to 583 B.C. But after careful researches of many competent authorities — Airy, Hind, Zech, Hansen, Ginzel, Newcomb, Cowell, Fotheringham and others — the date of May 28, 585 B.C., has been fixed, the eclipse taking place in the afternoon. The general consensus of opinion is that Thales was probably familiar with the Chaldean Saros of 223 lunar months or 18 years 11 days. In fact, by some it has been thought (*see*, George Smith, *Assyrian Discoveries*) that the Babylonians were actually making use of the Saros for the prediction of eclipses. Herodotus does not claim that the day and hour of the eclipse were predicted nor yet the locality where it was to be visible, these being much more difficult problems and incapable of being solved by Thales. The eclipse was predicted only "within the year." It is therefore not necessary to credit Thales with extraordinarily abnormal powers, or to assume that he was in possession of information which was known first to Hipparchus more than

four hundred years later. Apparently the Greek "wise man" utilized the eclipse of May 17, 603 B.C., for the purpose of his prediction.

Probably the greatest difficulty of all concerning the identification of this eclipse of Thales has been to know just how much credence could be placed in the account of Herodotus. Some of the ancient writers go so far as to accuse him of "intentional untruthfulness." Modern critics while not going to this extreme, none the less feel that his love of effect and his loose and inaccurate habits of thought make of him an attractive writer, but a poor historian. A case in point might be cited, the eclipse which is described by Herodotus (vii, 37) as follows: "At the first approach of spring, the army quitted Sardis and marched towards Abydos; at the moment of its departure the Sun quitted its place in the heavens and disappeared, though there were no clouds in sight and the day was quite clear; day was thus turned into night." We are told that "As the King was going against Greece, and had come into the region of the Hellespont, there happened an eclipse of the Sun in the East; this sign portended to him his defeat for the sun was eclipsed in the region of his rising, and Xerxes was also marching from that quarter." The generally accepted date of the battles of Thermopylae and Salamis is 480 B.C. No eclipse occurred in the spring of that year. Many attempts have been made to find an eclipse that would harmonize with the statement of Herodotus, but all of no avail, — unless we are willing to make changes either in the date or in the narrative. It seems necessary to conclude that the eclipse incident adds greatly to the attractiveness of the story, — but that it is not history. Unfortunately, even at the present day, authors still try to embellish their stories with celestial phenomena, but do not stick too closely to the facts. One of the "best sellers" appearing recently in the field of fiction had in it no less than four astronomical blunders.

The next eclipse to be mentioned was seen in Athens in B.C. 431, August 3. It is described by Thucydides (ii, 28) who states that during the Peloponnesian War "things formerly repeated on hearsay, but very rarely confirmed by

facts, became not incredible, both about earthquakes and eclipses of the Sun which came to pass more frequently than had been remembered in former times." An eclipse occurred in the first year of the war, "in the same summer, at the beginning of a new lunar month (at which time alone the phenomenon seems possible), the Sun was eclipsed after midday, and became full again after it had assumed a crescent form and after some of the stars had shone out." The account, differing from the flowery but uncertain language of Herodotus, is clear and definite, and refers to an eclipse which evidently was not total at Athens where Thucydides was supposed to be. The only difficulty in fixing the eclipse has arisen from the last part of the statement, that stars were visible. Venus was 10° distant and undoubtedly must have been readily seen, but what other star, or stars? The eclipse in B.C. 431 was seven-eighths total. To make a long story short, it sufficeth to say that at the eclipse of April 8, 1921, which was eight-ninths total at Oxford, the star Vega was readily seen. It must be concluded, therefore, that the account of Thucydides is strictly in accord with the facts and that the *stars* Venus, Vega and probably Jupiter 43° distant were seen.

This same eclipse has an interesting anecdote connected with it which has been narrated by Plutarch in his *Life of Pericles* who was the commander of the Grecian naval forces. "The whole fleet was in readiness, and Pericles on board his own galley when there happened an eclipse of the Sun. The sudden darkness was looked upon as an unfavorable omen, and threw the sailors into the greatest consternation. Pericles, observing that the pilot was much astonished and perplexed, took his cloak, and having covered his eyes with it, asked him if he found anything terrible in that, or considered it a bad presage? Upon his answering in the negative, he asked 'Where is the difference, then, between this and the other, except something bigger than my cloak causes the difference?'"

Another eclipse recorded by Thucydides (iv, 52) has been identified with the annular eclipse of March 21, 424 B.C.

The last of the eclipses described by Thucydides (vii 50)

is one of the moon, and it has a tragic story connected with it. The Athenian fleet and army were engaged in an attack on Syracuse, the fleet being under the command of Nicias, and Demosthenes had arrived with large reinforcements for the army. The latter had failed in his purpose of capturing a wall which the Syracusians had thrown across the Athenian lines, and as a result of this failure it had been decided to withdraw the whole Athenian forces. On the night of August 27, 413 B.C., the whole force had embarked and was ready to flee. Before a start was made, however, an eclipse of the moon took place which became total. Nicias was greatly terrified, for it seemed easy to understand the cause of an eclipse of the sun, but very difficult to make out " how the moon, when at the full, should suddenly lose her light and assume such a variety of colors." The soldiers and sailors added their terror to that of the commander and as a result the soothsayers were consulted. The advice was to remain for thrice nine days, — but alas, before that time the Athenians had been utterly routed, and Nicias and Demosthenes were both executed.

Plutarch records an eclipse of the sun which took place July 13, 364 B.C., and both Plutarch and Pliny give an account of a total eclipse of the moon September 20, 331 B.C., eleven days before the victory of Alexander over Darius at Arbela in Assyria.

Another interesting eclipse of the sun is connected with the name of Agathocles, the tyrant of Syracuse. The narratives of the two historians Justin and Diodorus Siculus agree so well that the astronomer has been able to fix exactly the circumstance of the eclipse. In 310 B.C. Syracuse was again besieged, this time not by Athens, but by Carthage. On the evening of August 14, Agathocles slipped out of the harbor with his whole fleet of sixty ships. He was pursued by the Carthaginians, who abandoned the chase at night-fall. According to the historical accounts, there was an eclipse of the sun on the following morning, and as a consequence day was turned into night, and stars appeared everywhere in the firmament. The soldiers were at first afraid, believing the eclipse to be an ill omen, but their fears were quickly calmed

by their commander who, according to Justin, told them that eclipses " always signify a change of affairs, and therefore some change was certainly signified, either to Carthage, which was in such a flourishing condition, or to them, whose affairs were in a very ruinous state." Apparently, these words of Agathocles seemed to have inspired his men that an eclipse might even be an omen for good. At any rate, he was able to make good his escape from the fleet of the Carthaginians, and after six days and nights he succeeded in landing on the coast of Africa and in devastating the territories of proud Carthage.

The readiness with which Agathocles and Pericles quieted the fears of the sailors calls to mind the genius of Columbus who, on more than one occasion, had to quell mutinies among the members of his little fleet, they being greatly perturbed on discovering that the compass needle did not point to the true north as given by the pole star.

Mention of only one other eclipse before the beginning of the Christian era will be made here. An eclipse is generally regarded to have taken place when Julius Caesar was crossing the Rubicon on his triumphal return to Rome from Gaul. But it seems to be necessary to class this eclipse along with that connected with the name Xerxes, — for it failed to occur.

In the investigations into the authenticity and accuracy of the early eclipses, the greatest difficulty has arisen from the vagueness and uncertainties of the account of the chronicler. References to eclipses are couched in such hazy language that the account might have been equally well applied to some other rare phenomenon. Writers of literature in all ages seem to prefer flowery to straightforward language and employ imagery rather than fact, refusing to " call a spade, a spade." For the astronomer it is impossible to take one interesting eclipse and decide on the *pros* and *cons* in favor of this or of that interpretation. Eclipses depend on the motions of the sun and moon, and the history of all eclipses must make a harmonious story and not a disjointed one. And so the eclipse of Agathocles must be considered in reference to that of Thales, and that in turn to the eclipse

of Nineveh in 763 B.C. The astronomer is not a dealer in necromancy nor does he acquire information about the motions of the sun and moon by mystical incantations, or by divination. The work of the scientist is as far removed as possible from the mountebank and charlatan. Scientific knowledge is acquired only by the patient study of all that has been accomplished in the past, and happy and fortunate is he who can make a correct interpretation of the past! The manner in which the story of eclipses has added to astronomical knowledge will be treated in a future chapter. Those who wish additional information regarding the early eclipses would do well to consult *Encyclopaedia Britannica*, article on *Eclipses* by Simon Newcomb, but specially the monumental work by Oppolzer, *Canon der Finsternisse*, which gives a record of no less than 13,200 eclipses, of which 5,200 are of the moon and 8,000 of the sun. These eclipses are the ones which have taken place since 1208 B.C., over three thousand years ago, or which will take place before the end of the year 2162 A.D., two hundred years in the future. In addition to the tables of the astronomical elements of each eclipse, 160 charts are furnished giving the location on the earth's surface where each total and annular eclipse of the sun will be visible. It should, however, be pointed out that the eclipse tracks could not be located by Oppolzer on the maps with the greatest of refinement, since it was manifestly impossible to calculate the location of each path for more than three positions, sunrise, noon and sunset. Consequently, it need not be a matter of surprise, particularly with the early eclipses, that the tracks may at times be incorrectly placed by as much as a hundred miles.

CHAPTER III

THE PREDICTION OF ECLIPSES

AFTER the destruction of Babylonia and Assyria, astronomy migrated from its Chaldean home to Greece. As early as the fifth century B.C., attempts were made to demonstrate some of the practical uses of astronomy in the regulation of time and particularly in the arranging of the calendar. The Greeks had inherited from the Chaldeans a calendar founded on the lunar month, but since the month is 29.5 days in length, attempts to bring the seasons and the calendar into harmony ended always in hopeless confusion. The astronomer Meton (born about 460 B.C.) made the discovery that 19 solar years were very nearly equivalent in length to 235 lunar months — the difference, in fact, being only about half an hour. The Metonic cycle, as it has since been called, has been of the very greatest service since its discovery so many centuries ago. It should not be confounded with the interval called the Saros, since the Metonic cycle is not used for the prediction of eclipses. After nineteen years, new and full moon and the various phases are repeated with a considerable degree of exactness. This cycle is still used for finding the day on which Easter will fall.

The Chaldeans had confined their energies to the making of astronomical observations, but their successors, the early Greek philosophers, made practically no observations whose record is worth keeping. On the other hand they were much interested in inquiring into the causes of things, and accordingly it may be said that the *science* of astronomy had its birth with the Greeks. We are already familiar with Thales and part of his work. To Pythagoras we owe the doctrine of the " music of the spheres," a notion which has descended even to the present day. To Plato (428–347

B.C.) astronomy owes but little, he even going so far as to decry, as degrading, the observation of the heavenly bodies. Far different, however, was the case with Aristotle (384–322 B.C.) who appears to have collected and systematized the best thought of the time regarding astronomy. He believed that all of the heavenly bodies, including sun, earth and moon, were spherical; he taught that the moon had no light of its own but shone by reflected sunlight and he explained its phases. Most important of these conclusions was the proof of the spherical shape of the earth. This, as Aristotle demonstrated, depends on two facts: first, that the earth casts a shadow and that an eclipse of the moon is due to the passing of the moon into this shadow; and second, that the shadow being circular in outline was proof that the body casting the shadow, the earth, was circular, at least in the section turned towards the moon.

After the time of Aristotle, Greek astronomy moved its home to Alexandria, and there under the protection of successive Ptolemies the great museum was erected and a library and an observatory were incorporated as important adjuncts. It is not the purpose here to trace the development of astronomy except as it progressed through the study of eclipses. The greatest astronomer of antiquity, in fact the most famous up to the time of Newton, was Hipparchus. He was not of Alexandria, though he probably visited the city and may have made some of his observations there. Little is known of his birth. This may have taken place in Bithynia or in Rhodes, though it is known that he had an observatory in the latter place and there did most of his work. We know of him mainly through the astronomer Ptolemy, since all of the original works of Hipparchus have been lost with the exception of one important book. His great fame rests upon three pedestals: (1) The invention of trigonometry, (2) the making of an extensive series of careful observations, (3) the comparison of his own with earlier observations. As a result of his exact and methodical work, he discovered the precession of the equinoxes, he made the first catalogue of the positions of stars (to the number of 1080), and he contributed greatly to the theory

of the motion of the sun and moon, and, as a direct consequence, to the subject of eclipses.

Hipparchus was the first to notice that the seasons were of unequal length, the time from vernal equinox to summer solstice being 94 days, while the summer season was only $92\frac{1}{2}$ days in length. Spring and summer together are seven days longer than fall and winter. Hipparchus gave the correct explanation of this fact, viz: that the earth is not always at a constant distance from the sun, being removed from the center of the orbit (which was then regarded as circular). At the present day this is readily verified by the change in the angular diameter of the sun, — but this confirmation in Hipparchus' time would have required measurements too exact for his crude instruments. By noting the time it takes the moon to pass through the earth's shadow at the time of a total eclipse of the moon, Hipparchus was able, by a method due to Aristarchus, to obtain a value of the relative sizes of earth and moon, and also to estimate the distance of the moon to be 59 times the terrestrial radius, — which is not very far from the truth.

The motion of the moon was much more difficult to investigate than that of the sun. Little observation is necessary to note that the moon moves eastward in the sky, changing her position among the stars by her own diameter in approximately an hour. A revolution of the moon from a star to the same star again is known as a *sidereal* month, and its length is 27.3 days. In this interval the earth has gone forward in her orbit, and more than two additional days are necessary for the moon to overtake the earth as it passes forward in its annual journey about the sun. The interval of time from new moon to new moon, or from full moon to full moon, is the ordinary month of 29.5 days, called the *synodic* month. Further observation shows that the sun is always in the ecliptic, in fact, the sun's apparent motion determines the ecliptic, whereas the motion of the moon, although approximately in the ecliptic, is nevertheless inclined at a small angle, which Hipparchus for the first time fixed as at an angle of 5°. The moon's path thus crosses the ecliptic at two points called the nodes. If the

moon's path were exactly in the plane of the ecliptic there would be two eclipses each month, once at the time of new moon when the moon would come between the earth and the sun, bringing about an eclipse of the sun; and again at full moon, when the moon would pass into the shadow cast by the earth and be itself eclipsed. But as the moon's orbit is inclined to the ecliptic, it is manifest that eclipses, either of sun or moon, can occur only when the moon is near the plane of the ecliptic, or, in other words, near its node. If the length of time it takes the moon to return to its node were the same as the sidereal month, it is evident that the moon's node would be fixed in space and would have no motion relative to the stars. The length of the month determined by the return of the moon to the node is called the *nodical,* or the *draconic* month. The meaning of the first designation is evident. But why the second? It is not difficult to trace it back to the ancient belief that the sun was swallowed by a dragon at the time of an eclipse, and this superstition is therefore the reason why the month on which eclipses depend should be called draconic. Indeed the symbols that are universally used by astronomers to denote the ascending node (☊) and the descending node (☋) are generally supposed[1] to represent the head and tail of the dragon. Hipparchus found that the moon's nodes were not fixed, but that they completed a revolution in the plane of the ecliptic from east to west in about 19 years. A fourth kind of month was likewise known to Hipparchus, the length of a revolution from the position of perigee to perigee in the moon's orbit. By making use of the eclipses observed by the Chaldeans, Hipparchus was enabled to obtain greatly improved values of the lengths of the various months. The values that follow are those furnished by the recent investigations of E. W. Brown:

Synodical	= $29.^d530588$	= 29^d	12^h	44^m	$2.^s8$
Sidereal	= 27. 321661	= 27	7	43	11. 5
Anomalistic	= 27. 554550	= 27	13	18	33. 1
Nodical	= 27. 212220	= 27	5	5	35. 8

[1] See Berry, *A Short History of Astronomy,* p. 48.

The lengths of the different kinds of year will be inserted here for future reference, the values being Newcomb's:

Tropical (ordinary)	= $365.^d242199$
Eclipse	= 346. 620031

Since the motion of the moon's node is in the direction to meet the oncoming sun, the interval of time from node to node (the eclipse year) is less than the interval from vernal equinox to vernal equinox, the ordinary year on which the seasons depend. From the above figures, the eclipse year is 18.62 days shorter than the tropical year. Since the sun and earth are always in the plane of the ecliptic, all that is required to permit the prediction of an eclipse of the sun is to find *at the time of the new moon* (when alone a solar eclipse can take place) whether the moon is sufficiently near enough to the plane of the ecliptic for her to come between earth and sun. And as an eclipse of the moon can happen only *at full moon,* similar investigations will furnish the means of predicting lunar eclipses. With the modern values given above, these predictions can be carried out remarkably easily. Let us see:

19 eclipse years	= $6585.^d7806$
223 ordinary months	= 6585. 3211
247 nodical months	= 6585. 3572
239 anomalistic months	= 6585. 5374

The integral parts of these four quantities are the same, the second being the *Saros* (meaning "repetition") which amounts to 18 years 11 days, if only four leap years intervene, or 18 years 10 days if the 29th of February has come five times. The eclipse of June 8, 1918 was a repetition of that of May 28, 1900; the eclipse of September 10, 1923 follows that of August 30, 1905 by the interval of one Saros. The author observed the 1900 eclipse in Georgia and that of 1918 in Oregon. It was necessary for him to travel to Spain to witness the 1905 eclipse and to California for the one of 1923. Succeeding eclipses in the Saros are visible each time from a location on the earth's surface farther west. The reason for this, and the causes of further differences in eclipses which follow each other are

readily explained from the fact that the numbers given above are not exactly equal to each other but differ in the decimal parts. Before going into this in detail, it will be well to take up some of the geometrical features useful in the prediction of eclipses.

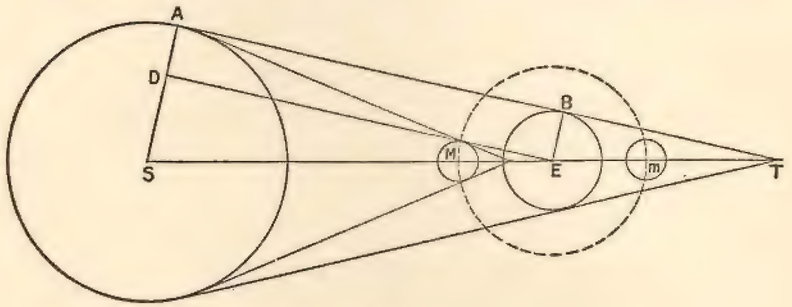


FIG. 1

The length of the shadow cast by earth or moon can be readily found. S is the center of the sun, E that of the earth, and M and *m* the moon's center at new and full moon, respectively. A shadow cone envelopes the sun and earth, its vertex being at T. If the moon in her orbit passes wholly into the shadow there is a total eclipse of the moon. If the line ED is drawn parallel to TBA, then it is seen that the triangle DSE and BET are similar, and hence

$$\frac{ET}{EB} = \frac{SE}{SD}$$

But $SD = SA - AD = R - r$, if R and r denote the radii of sun and earth respectively. SE is the distance of sun to earth which equals Δ. Hence the length of the shadow,

$$ET = \frac{r}{R-r}\Delta$$

But R, the radius of the sun, is equal to 109.5 times the radius of the earth, r, and accordingly, the length of the earth's shadow is equal to

$$\frac{\Delta}{108.5}$$

Assuming the average value of the distance from sun to earth as 92,900,000 miles, then the length of the earth's shadow is on the average 857,000 miles, the distance of the earth to moon being much less than this, or 238,840 miles.

In quite a similar manner it is possible to find the length of the shadow cast by the moon, by taking the moon instead of the earth, and assuming C as the length of the moon's radius, and D the distance from centers of sun to moon. The length of the shadow cast by the moon is equal

$$\frac{C}{R-C} \cdot D$$

But R and C, the radii of the sun and moon, are each constant, and substituting the values it is found that the length of the moon's shadow is $\frac{1}{399.55}$ of the moon's distance from the sun, or approximately one four-hundredth part of the distance. Under the conditions giving a total eclipse of the sun, the distance from sun to moon, D, is equivalent to the differences between the distances from sun to earth and from earth to moon. On account of the fact that the orbits of earth and moon are both ellipses and not circles, the distance D will vary considerably and the length of the moon's shadow will change proportionally. Under *average* conditions, the length of the shadow measured from the center of the moon is 231,650 miles, but this may vary about 4000 miles each way from the mean, or from 235,700 miles as a maximum to 228,120 miles as a minimum. Since the mean distance from center of earth to center of moon is 238,840 miles, or from moon's center to earth's *surface* 234,900 miles, it is seen that under average conditions the moon's shadow is not long enough to reach the earth's surface. The distance D will have its greatest value when the earth is at its greatest distance from the sun, at aphelion, which takes place about July 1 of each year, and the moon at its least distance from the earth, or at perigee. Owing to the revolution of the moon's line of apsides, perigee may come during any month of the year. The distance D is least when the earth is at perihelion (January 1) and the moon at apogee. On account of the

elliptical character of the moon's orbit, the distance from center of earth to center of moon varies, from approximately 253,000 miles as a maximum to 221,600 miles as a minimum. The latter distance is 217,650 miles from the earth's surface. Since the shadow cast by the moon may be 235,700 miles in length, its vertex therefore at times may extend 18,000 miles beyond the earth's surface. Under these conditions the area of the moon's shadow cone intercepted by the earth will be a maximum, and when all conditions are most favorable, the diameter will be 167 miles. Such conditions are possible when the total eclipse is visible about July 1, with the moon at perigee, the eclipse being visible at the earth's equator at noon. The diameter of the moon's shadow path intercepted by the earth may vary from its maximum value to a vanishing width when the shadow is just long enough to reach the earth's surface. The average width is approximately one hundred miles. Inside this shadow cone an observer will see the light of the sun totally cut off; outside of it the sun will be partially eclipsed.

Since also the distance may be as great as 253,000 miles from the earth's center, or about 249,000 miles from its surface, while the moon's shadow may be only 228,120 miles in length, the shadow may fall short of the earth's surface by more than 20,000 miles. Under these conditions an observer on the earth located on the axis of the shadow produced, would see an annular eclipse and not a total one, a ring or annulus of light appearing round the edge of the moon when the eclipse is central. The diameter of the so-called negative shadow may be as great as 230 miles. Since the maximum width of the shadow causing a total solar eclipse is only 167 miles, it is evident that the number of annular eclipses are more frequent than total, — only two out of five central eclipses being total.

The work of the observational astronomer has been greatly hampered by the moon which illuminates the sky and renders it impossible to see or to photograph the faintest stars in the telescope. As already has been noted, the moon has furnished much labor and vexation of spirit to the mathematical astronomer. Yet if our satellite were

banished from the sky, what a dreary old world it would be to poets and lovers without their " inconstant moon "! If the diameter of the moon were decreased a scant hundred and forty miles (less than seven percent), a total eclipse of the sun would be impossible! How thankful solar astronomers should be for the strange coincidence that the angular diameter of the moon is about equivalent to that of the sun and that the diameter of the moon is not ten percent less than it is! The greatest possible excess of the angular radius of the moon over that of the sun is only $1' \, 19''$.

Knowing the diameter of the shadow intercepted by the earth it is easy to find the duration of totality. For this purpose it is necessary to find the speed of the shadow over the earth. The moon advances in her orbit approximately her own diameter in an hour, or more exactly, about 2100 miles per hour. On account of the great distance of the sun, this is the speed that the moon's shadow passes across the earth regarded as a whole, but on account of the rotation of the earth on its axis the velocity of the moon's shadow over the earth's surface is far different from 2100 miles per hour. The diurnal rotation causes an observer at the equator to complete a circuit of nearly 25,000 miles in twenty-four hours which is at the rate of 1040 miles per hour. Away from the equator, farther north and south in latitude, the speed is progressively less at greater and greater distances from the equator, being in fact 1040 miles per hour multiplied by the cosine of the latitude. At 30° north and south an observer is carried 900 miles per hour, at 45° only 735 miles, while at 60° this is reduced to 500 miles. The moon moves in her orbit from west to east and her shadow in consequence traverses the earth in this direction also. This being likewise the direction that an observer is carried by the earth's rotation, the moon's shadow path travels with respect to the earth's surface the difference of the two speeds, which is 1060 miles at the equator, and 1600 miles at latitude 60°.

The above values refer only to the condition that the eclipse occurs on the meridian for the observer in question,

or in other words, at noon. When the eclipse takes place near sunrise or sunset, the observer being turned not directly towards the sun and moon, the projection of the moon's orbital velocity along the earth's surface may be very large. The slowest speed that the moon's shadow can have over the earth's surface is 1060 miles per hour, when the eclipse occurs at noon and at the equator, and the speed under conditions of higher latitudes and eclipse at sunrise or sunset may be as great as 4000 or even 5000 miles per hour. With the conditions causing maximum width of shadow of 167 miles, an eclipse of the sun may be total for a time which at best is very short, amounting as it does to seven and a half minutes. Even a six-minute eclipse, such as the Sumatra eclipse of May 18, 1901 and its repetition eighteen years later in Brazil and Africa, is considered by astronomers unusually long.

The discussion above regarding the conditions of a solar eclipse has been made with reference to the *umbra* of the moon's shadow. An observer on the earth situated within the confines of this shadow would find the sun's light totally obscured. Inside the *penumbra* of the moon's shadow, the sun is not entirely covered up by the moon and a partial solar eclipse will result. The diameter of the penumbra intercepted by the earth is readily determined. Since the angular diameters of sun and moon are nearly equal, the diameter of the penumbra measured at right angles to the line joining sun and moon is about twice the diameter of the moon, or roughly 4400 miles. Consequently, for a distance of 2200 miles along the earth's surface on either side of the moon's umbra a partial eclipse may be visible. And by a process of reasoning similar to that followed out in the case of total eclipses, it is readily perceived that in latitudes away from the equator and when the eclipse is at sunrise or sunset, the distance along the earth's surface when a partial solar eclipse is visible may be increased to 3000 miles from the central line of totality.

Again, since the sun and moon's angular diameters are about equal, and the moon moves the extent of her diameter in an hour, it will take about one hour from the first

beginning of an eclipse to the beginning of totality, or, as the astronomer expresses it, from first to second contact. Similarly an hour will elapse between third and fourth contacts, or between the ending of totality and the end of the eclipse.

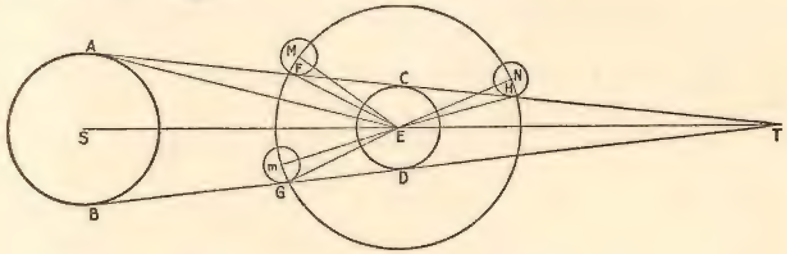


FIG. 2

For an eclipse of the *sun* to occur, it is necessary for the moon at M to encroach on the shadow-cone $ACDB$ enveloping sun and earth. The angle between sun and moon under these conditions is readily determined. The angle SEM in Fig. 2 is the sum of three angles SEA, AEF and FEM. SEA and FEM are the angular semi-diameters of sun and moon respectively, while the angle AEF is equal CFE–CAE. But CAE is the angle subtended by the earth's radius at the distance of the sun, and is accordingly the sun's horizontal parallax. If S and s represent the angular semi-diameter of sun and moon, and P and p the horizontal parallaxes of sun and moon respectively, then MES is equal to $S+s-P+p$.

For the solar eclipse to be *total*, the moon must be entirely within the shadow at m, and for these conditions the angle SEm is found to be $S-s-P+p$.

For an eclipse of the *moon*, with moon at N, the angle between the moon and the center of the earth's shadow, the angle NET is equal $NEH + HET = NEH + CHE - HTE$. But $SEA = EAT + HTE$, hence $NET = S + p - S + P$.

Since the centers of the sun and moon are always in the ecliptic, the angles just determined give the amount in angle that the moon may be distant from the ecliptic at the time of new or full moon in order that there may be an

eclipse of sun or moon. Angular distances measured at right angles to the ecliptic are called celestial latitudes, and hence in order that a partial eclipse may take place, the latitude of the moon must be less than

$$p + s + (S—P) \quad \text{for a } \textit{solar} \text{ eclipse,}$$
$$\text{and } p + s — (S—P) \quad \text{for a } \textit{lunar} \text{ eclipse.}$$

Since S has a mean value of 32′, while P is never greater than 9″, it is evident that a solar eclipse can take place with the moon at a greater angular distance from the ecliptic than is possible for an eclipse of the moon. This is patent by referring to Fig. 2 and noting that a section across the shadow-cone enveloping sun and earth is greater through the moon at new moon, i.e., for a solar eclipse, than at full moon, or for a lunar eclipse.

For the conditions under which total eclipses may occur, we find that the celestial latitudes of the moon at the time of conjunction of sun and moon are (by changing $+ s$ to $— s$ in the above formula)

$$p — s + (S—P) \quad \text{for } \textit{total solar} \text{ eclipse,}$$
$$\text{and } p — s + (S—P) \quad \text{for } \textit{total lunar} \text{ eclipse.}$$

On account of the varying distances of sun and moon from the earth, the values of the semi-diameters and parallaxes of sun and moon are changing proportionally. In the table below the values are taken from the *American Ephemeris:*

	Greatest	*Least*	*Mean*
Semi-diameter of sun $= S$	16′ 18″	15′ 46″	15′ 59″.6
Semi-diameter of moon $= s$	16′ 46″	14′ 43″	15′ 32″.6
Horizontal parallax of sun $= P$	8″.9	8″.7	8″.8
Horizontal parallax of moon $= p$	61′ 28″	53′ 55″	57′ 2″.7
Inclination of moon's orbit $= i$	5° 19′	4° 57′	5° 8′ 43″

An eclipse, either of sun or moon, may be predicted by finding from the above formulas the moon's celestial latitude. For purposes of computation it is more convenient to find the angular distance that the sun or moon may be from the moon's node, but measured in the plane of the ecliptic. These angles, being celestial longitudes, determined at the time of new moon give what is known as the *solar ecliptic limit*, and at full moon furnish the *lunar ecliptic limit*. In Fig. 3, NS is the ecliptic, MN the moon's path, N the moon's ascending node. M is the moon, and the circle at S, for a solar eclipse, represents a section of the shadow cone at M (in Fig. 2), and, for a lunar eclipse, a section through N (in Fig. 2), The angle SNM represents the angle, i, of inclination of the moon's orbit to the plane of the ecliptic.

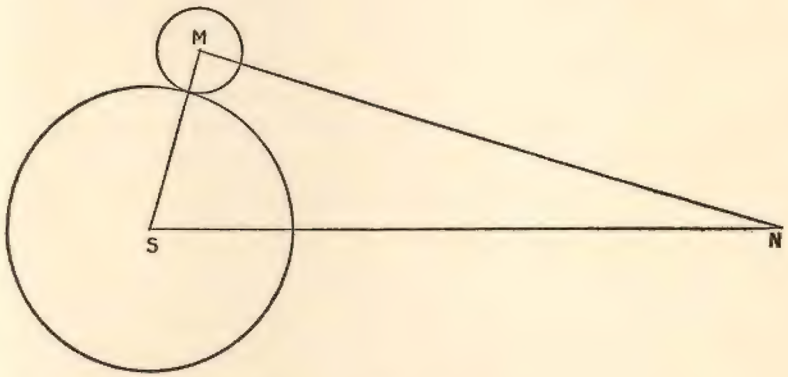


FIG. 3

For a solar eclipse, the angular distance SM is known from above as equal to $p + s + S—P$. The angle i is known, and if the angle at S is assumed as a right angle the triangle SNM can be solved, and the distance SN determined. An approximate method is all that is required, and since the mean value of i is nearly one-eleventh of a radian, hence SN, the ecliptic limit is approximately eleven times SM. But as the value of SM depends on the semi-diameters and parallaxes of sun and moon, and as we have seen these quantities continually are varying, the value of the ecliptic limit must also vary proportionally, and also because the angle i changes likewise. Hence it is necessary to distinguish between the maximum and minimum values of the ecliptic limit, for solar and lunar eclipses and for total and partial eclipses. Using the appropriate maximum and min-

imum values, it is easy to find the following values of eclipse limits.

	Major	Minor
Solar eclipse	18° 31′	15° 21′
Lunar eclipse	12° 15′	9° 30′
Total solar eclipse	11° 50′	9° 55′
Total lunar eclipse	6° 0′	3° 45′

The method of using these quantities for the purpose of predicting eclipses is very simple. All of the necessary additional information is readily obtainable from one of the government publications like the *American Ephemeris and Nautical Almanac.* As already stated, an eclipse of the sun can take place only at new moon. For this instant of time look up in the *Ephemeris* the longitude of the sun and that of the moon's node. The difference is the angular distance of the sun from the node. If this longitude is greater than the major ecliptic limit of 18°31′, an eclipse of the sun cannot possibly take place; if the quantity is less than the minor limit of 15°21′, an eclipse must certainly take place. If the difference in longitudes is less than 18°31′, but greater than 15°21′, it is impossible to state whether an eclipse will take place or not, and recourse must then be had to a calculation of the ecliptic limit using the particular values for the semi-diameters, parallaxes and inclination for the day in question at the time of new moon. The conditions for a *total* eclipse are found by using the major and minor ecliptic limits of 11°50′ and 9°55′. Similarly, for an eclipse of the moon, which occurs only at full moon, by utilizing the values of the lunar ecliptic limits, it is possible to predict whether an eclipse of the moon will happen or not.

Ordinarily, however, instead of using these simple mathematical formulas and referring to the *Ephemeris,* it is much simpler to employ the *Saros* for the purpose of predicting eclipses. All of the various series of eclipses, lunar and solar, that are taking place at the present time are well known to the astronomer, and all that is necessary to forecast each eclipse is to bring forward the data by utilizing the duration of the Saros. A method even still simpler than this is to refer to such a book as Oppolzer's *Canon der Finsternisse*

where are given the elements of all of the eclipses (8000 solar and 5200 lunar) between the dates 1208 B.C. and 2162 A.D. Various lists of total solar eclipses have been published. (See for instance, *Encyclopaedia Britannica,* article on *Eclipses*).

Referring now to the lengths of the different kinds of months on p. 40, we recall that 19 returns of the sun to the moon's node are equal to 6585.7806 days, while 223 synodic months consume the slightly different amount of 6585.3211 days. If therefore a new moon fell exactly at the node, then after 18 years 11 days, the new moon would take place before the node was reached. The difference of the two quantities above is 0.4595 days, in which time the sun moves 28′. Accordingly, at each succeeding Saros the new moon is found 28′ farther and farther west of the node. It is now possible to trace the total number of eclipses and the progressive changes in them as they pass through the Saros. According to the value of the ecliptic limit already found, we know that if the new moon happens within 18° of the node, an eclipse of the sun may take place. If the node is the ascending one, the conditions will be as represented in Figs. 3 and 2, the moon being north of the shadow-cone. An eclipse of the sun will accordingly be visible in high northern latitudes on the earth. After 18 years 11 days the conditions will be nearly identical, but the new moon will take place 28′ nearer the node, and as a result, the eclipse will be visible on the earth a little farther south of the preceding position. With each succeeding return, the new moon moves nearer and nearer the node and the eclipse track shifts farther and farther south on the earth. When the moon is within about 11° of the node the solar eclipse becomes central, and the eclipse may be total or annular. As before, the central eclipse track will first touch only high northern latitudes, each succeeding eclipse moving farther and farther to the south. Total or annular eclipses will now take place at each return of the Saros until the new moon takes place 11° west of the node, when the central eclipse track passes off the earth at its south pole, and a series of partial

eclipses then ensues until the moon is 18° west of the node, when these particular eclipses cease altogether. In such a series there are anywhere from 68 to 75 eclipses, depending on conditions, extending over some 1200 years. Of these, 25 are partial eclipses, the moon not getting entirely into the shadow-cone enveloping sun and earth (Fig. 2), and 45 are central, of which number about 18 are total, and 27 annular. The numbers vary somewhat for different series of eclipses. If the eclipses had taken place at the descending node of the moon's orbit instead of at the ascending node, eclipses would then have come on the earth at its south pole and gradually moved north, going off the earth at the north pole.

On account of the ecliptic limits for lunar eclipses being smaller in value than for solar eclipses, there will be fewer repetitions in a lunar series, there being 48 or 49 altogether. Of this number there will be 22 or 23 total, with 13 or 14 partial eclipses, both before and after the total eclipses. The interval for a series of lunar eclipses consumes about 870 years.

There is one other very important relation brought out by the data on page 41. It is there found that 239 returns of the moon to the line of apsides, or to perigee, amount as a total to 6585.5374 days. For predicting the nature of the eclipse that will be found at the next return this quantity is almost as valuable as the Saros itself. At the end of 223 lunations the moon not only returns very closely to its original position with respect to the sun and the node, but also with respect to the line of apsides, with the necessary result that the distance from earth to moon is very closely repeated. This fact in turn brings two consequences; firstly that the duration of the eclipse, or at least that part of it which depends on the moon's distance, is altered but little; but secondly, that the perturbations of the moon's orbit which otherwise might have displaced by several hours the time of the eclipse will now be repeated almost as they were before, and with no consequent relative effect on the time of the eclipse.

CHAPTER IV

THE VERIFICATION OF ECLIPSES

IN THE last chapter it was shown that with great ease the times of eclipses can be accurately foretold by means of the Saros. Equally important with the actual prediction of the times is the fact that the circumstances attending the eclipses following each other in the Saros will be very closely repeated. A large partial eclipse of the sun will be followed by a large partial eclipse of the sun, an annular eclipse by an annular eclipse, a total eclipse of short duration by a similar short eclipse. And so also with lunar eclipses. There remains still to explain the signification of the decimal portion of the time of the Saros, 6585.3211 days. If the sun had been on the meridian at the middle of the eclipse, the eclipse therefore occurring at noon, the next following eclipse will be repeated at a place 0.3211 of a revolution of the earth, or in other words 7h. 42m. of longitude farther west. After the return of three Saroses, or 54 years, the eclipse tracks will have gone almost around the world and will have returned again to nearly the same longitude. If the eclipses belong to a series that is taking place at the moon's ascending node, the later eclipse track will be found farther south than the earlier one, and if at the descending node, farther north than the eclipse fifty-four years earlier.

Those who wish to amuse themselves by playing with figures may find other remarkable coincidences by experimenting with the lengths of the various years and months on p. 41. Newcomb has found a very interesting period at the end of 358 lunations.

358 synodic months	=	10571.95 days
30.5 eclipse years	=	10571.91 days

This period amounts to 29 Julian years, less 20.3 days. But 358 lunations are equal in length to 383.673 anomalistic months, and hence, as explained in the preceding chapter, the eclipses which follow each other with this period will differ greatly in their characteristics, since the conjunctions between sun and moon take place at different positions with respect to perigee. Also, such eclipses must follow each other alternately at ascending and descending nodes. Three such periods, however, will equal 1169.019 anomalistic months, and the time of conjunction has accordingly moved very close to perigee (if it had previously been found there) and a total eclipse will thus be followed by a total eclipse. Three of these periods equal 87 years less 61 days, and 18 periods equal 521 years, actually within a day or two. Thus with the Saros of 18 years, and with the addition of the 29-year, the 87-year and the 521-year periods, the astronomer is enabled to engage in predicting at long range. Take for instance the first eclipse verified with certainty, the Nineveh eclipse of June 15, 763 B.C. (763 B.C. may be expressed also as the year —762). Applying the 521-year period we have the years 242 B.C. and A.D. 280, 801, 1322 and 1843. These eclipses each fell on June 15, O. S., or by the Julian calendar. The date of June 15, 1843, O. S., is the same as June 27, 1843, by the Gregorian or present-day calendar. By means of the 29-year period we obtain the eclipses of June 6, 1872, and May 18, 1901. (The eclipses of 1843 and 1872 were not total while that of 1901 was the six-minute total eclipse observed in Sumatra.)

In the following table are given one hundred years of total eclipses of the sun.[1]

[1] See, *Encyclopaedia Britannica*, article on *Eclipses* by Simon Newcomb.

Date	*Series*	*Node*	*Duration*	*Where visible*
1875, April 6	1	A	4.7 *m.*	Indian Ocean, Siam, Pacific.
1876, Sept. 17	2	D	1.8	Pacific Ocean.
1878, July 29	3	D	3.2	United States and Canada.
1880, Jan. 11	4	A	2.1	Pacific Ocean, California.
1882, May 17	5	D	1.8	Egypt, Central Asia, China.
1883, May 6	6	D	6.0	Pacific Ocean, Caroline Islands.
1886, Aug. 29	7	A	6.6	South America, Central Africa.
1887, Aug. 19	8	A	3.8	Northern Europe, Siberia, Japan.
1889, Jan. 1	9	D	2.2	California, Oregon, British America.
1889, Dec. 22	10	D	4.2	Central Africa and South America.
1893, April 16	1	A	4.8	Venezuela to West Africa.
1894, Sept. 29	2	D	1.8	East Africa, Indian Ocean.
1896, Aug. 9	3	D	2.7	North Europe, Siberia, Japan.
1898, Jan. 22	4	A	2.3	East Africa, India, China.
1900, May 28	5	D	2.1	United States, Spain, North Africa.
1901, May 18	6	D	6.5	Sumatra, Borneo.
1904, Sept. 9	7	A	6.4	Pacific Ocean.
1905, Aug. 30	8	A	3.8	Canada, Spain, North Africa.
1907, Jan. 14	9	D	2.3	Russia, Central Asia.
1908, Jan. 3	10	D	4.2	Pacific Ocean.
1911, April 28	1	A	5.0	Australia, Polynesia.
1912, Oct. 10	2	D	1.8	Colombia, Ecuador, Brazil.
1914, Aug. 21	3	D	2.1	Scandinavia, Russia, Asia Minor.
1916, Feb. 3	4	A	2.5	Pacific Ocean, Venezuela, West Indies.
1918, June 8	5	D	2.4	British Columbia, United States.
1919, May 29	6	D	6.9	Peru, Brazil, Central Africa.
1922, Sept. 21	7	A	6.1	East Africa, Australia.
1923, Sept. 10	8	A	3.6	California, Mexico, Central America.
1925, Jan. 24	9	D	2.4	United States.
1926, Jan. 14	10	D	4.2	East Africa, Sumatra, Philippines.
1927, June 29	11	A	0.7	England, Scotland, Scandinavia.
1929, May 9	1	A	5.1	Sumatra, Malacca, Philippines.
1930, Oct. 21	2	D	1.9	Pacific Ocean, Patagonia.
1932, Aug. 31	3	D	1.5	Canada.
1934, Feb. 14	4	A	2.7	Borneo, Celebes.
1936, June 19	5	D	2.5	Greece to Central Asia and Japan.
1937, June 8	6	D	7.1	Pacific Ocean, Peru.
1940, Oct. 1	7	A	5.7	Colombia, Brazil, South Africa.
1941, Sept. 21	8	A	3.3	Central Asia, China, Pacific Ocean.
1943, Feb. 4	9	D	2.5	China, Alaska.
1947, May 20	1	A	5.2	Argentina, Paraguay, Central Africa.
1948, Nov. 1	2	D	1.9	Central Africa, Congo.
1952, Feb. 25	4	A	3.0	Nubia, Persia, Siberia.
1954, June 30	5	D	2.5	Canada, Scandinavia, Russia, Persia.

Date	*Series*	*Node*	*Duration*	*Where visible*
1955, June 20	6	D	7.2 *m.*	Ceylon, Siam, Philippines.
1958, Oct. 12	7	A	5.2	Chile, Argentina.
1959, Oct. 2	8	A	3.0	Canaries, Central Africa.
1961, Feb. 15	9	D	2.6	France, Italy, Austria, Siberia.
1962, Feb. 5	10	D	4.1	New Guinea.
1963, July 20	11	A	1.5	Alaska, Hudson Bay Territory.
1965, May 30	1	A	5.3	Pacific Ocean.
1966, Nov. 12	2	D	1.9	Bolivia, Argentina, Brazil.
1970, Mar. 7	4	A	3.3	Mexico, Florida.
1972, July 10	5	D	2.7	Northeast Asia, Northeast America and Atlantic Ocean.
1973, June 30	6	D	7.2	South America, Africa and Atlantic Ocean.
1974, June 20	12	D	5.3	Southwest Australia and Indian Ocean.

The durations of totality of the eclipses in series 6 and 7 are greater than those of the balance. In 1955, conditions combine to make totality last almost to its maximum possible extent. It will be noticed from the table that total eclipses which have been, or will be visible in the United States are: 1878, July 29; 1880, January 11; 1889, January 1; 1900, May 28; 1918, June 8; 1923, September 10; 1925, January 24; 1970, March 7. Manifestly the coming half century sees few opportunities in the United States for the observation of such eclipses. The eclipse of 1923 is visible in its total phase in a very small area of the mainland of the United States, the extreme southwestern corner of California being the only section within the moon's shadow path. In 1925, the eclipse track will be found about midway between New York and Boston, but unfortunately, the eclipse occurs with the sun not very far above the horizon, and, as further obstacles to be overcome, the cold and the cloudy weather usually prevalent in New England on January 24 do not bespeak successful observations. A period of no less than forty-five years then elapses before the eclipse of March 7, 1970. In the United States the eclipse will be visible only in Florida, and the chance of clouds and rain will be very great. The next eclipse after that will be on February 26, 1979, visible in Northwest United States and in Canada across Hudson's Bay. What hardy astronomer

will be willing to brave the probabilities of a blizzard and 40° F. below zero in order to add to scientific knowledge by observing this total eclipse? It thus appears that after the eclipse of 1923 has passed into memory there will not be an opportunity to view a total eclipse of the sun from the continent of the United States, under conditions that are really favorable and promise scientific success, until the eclipses of August 21, 2017, and April 8, 2024. Apparently the coming generations of American astronomers will be forced to travel away from home if they wish to make observations of total eclipses. It is not impossible that before the year 2017 the astronomers of the future will have solved all of the problems connected with eclipses. As is the case with the prominences of the sun which are no longer purely eclipse phenomena, the coming generation may have found methods of investigating chromosphere and corona with such success that observations at eclipses will no longer be necessary. When science shall have progressed to this extent, future astronomers will be able to point to the long trips taken by their forefathers, sometimes half way round the globe, in order to observe a total eclipse for a few brief minutes of time. In the twenty-first century the great god of Efficiency may be worshipped even more profoundly than is the case in the beginning of the twentieth century. Under such circumstances a total eclipse will still be viewed with interest as a fascinating phenomenon, which, however, will afford ample evidence of the crude methods of investigation of the astronomers a century before.

If so few eclipses are visible in such a large country as the United States, how about those in a relatively small territory like the British Isles? The eclipse of June 29, 1927, will cross Ireland, northern England and southern Scotland, but the eclipse will be barely total; that of August 11, 1999, grazes the south of Ireland and Land's End, and on August 12, 2026, the eclipse track may cross the southwestern tip of Ireland but will not be seen in Great Britain.

Since the sixth century the following total eclipses have touched parts of the British Isles:

594 July 23	1185 May 1
603 Aug. 12	1330 July 16
639 Sept. 3	1424 June 26
664 May 1	1433 June 17
878 Oct. 29	1598 Mar. 6
885 June 15	1652 April 8
1023 Jan. 24	1715 May 2
1133 Aug. 1	1724 May 22
1140 Mar. 20	

Eclipses have included London twice, Dublin twice, and Edinburgh five times.

On the other hand, some parts of the globe are visited by eclipses in rapid succession. Spain witnessed the eclipses of 1842, 1860, 1870, 1900 and 1905. In the East Indies the eclipse of 1901 was observed, and those of January 14, 1926, May 9, 1929, and February 14, 1934, will be possible, while the track of the eclipse of September 21, 1922, lay but a few hundred miles south.

Assuming that the moon's shadow path intercepted by the earth averages 100 miles in width, it is easy to find that on the average a total eclipse of the sun will be visible in any one locality once every 360 years. A stay-at-home astronomer might have little opportunity during his lifetime to witness many such eclipses!

With a knowledge of the lunar and solar ecliptic limits it is possible to find the number of eclipses that will occur in any given time, say a year. If at the time of the new moon, the moon (and also the sun) is more than 18° 31′ from the moon's node there cannot possibly be an eclipse of the sun. Since the angle of 18° 31′ may be east or west of the node, there is thus a zone of 37°, within which an eclipse of the sun *may* take place provided that a new moon also occurs somewhere within the zone. The minor ecliptic limit for a solar eclipse is 15° 21′, and similarly if new moon is found anywhere in the zone 30° 42′ in length an eclipse of the sun *must* happen, there being no possibility of the moon slipping by without intercepting the light from the sun as it comes in the direction towards the earth. For an eclipse of the moon, the ecliptic limits are smaller. It is only when full moon comes with 9° 30′ of the node that a

lunar eclipse is certain to take place, though an eclipse may possibly happen if the limit is as great as 12° 15′. In a synodic month the moon moves along the ecliptic to an average extent of 29° 6′. But the moon's node is also moving, and in the opposite direction by an amount of 1° 31′ during the progress of the month. *Relative to the node,* the moon therefore moves the sum of 29° 6′ and 1° 31′, or 30° 37′ in a synodic month, and it is this motion relative to the node on which the circumstances of an eclipse depend. By an analogy one can see how easily the question of eclipses is thought out. Suppose a man walking around a circular track of any diameter in which there are two mud holes four feet in width diametrically opposite each other. If he is taking a constant pace of three feet, it will be impossible for him to walk around the track without stepping at least once into each mud hole during each circuit. If when he comes to the muddy spot he happens to plant his foot near the middle he will have only one wet foot, but if the first foot gets in the hole near the edge, the second foot may be planted in the mud near the other side of the puddle. If the mud hole were only two feet in width, his standard pace of three feet might carry him across it without either foot getting into the mud. And so it is with eclipses of sun and moon. The moon's step is 30° 37′ in angular length, the danger zone for a solar eclipse is 30° 42′, or a quantity which is larger than the moon's monthly motion with respect to the node. There *must,* therefore, be at least one solar eclipse at each nodal point, or two such eclipses without fail during the course of each and every year. On the other hand, the danger zone for lunar eclipses being much smaller, it is possible that the full moon may take place so far from the node each time that there will not be a single lunar eclipse during the year. There can, moreover, be only one eclipse of the moon at each node, but never two. Eclipses do not occur in the same months each year, but follow each other at the beginning and end of the "eclipse year" of 346.6 days. This being 18 days less than the calendar year it is possible for there to be three eclipses of the moon within the calendar year, if the node is passed

early in January, or late in December (which comes to the same thing). Two solar eclipses may possibly take place at each node, and a fifth one within the calendar year. If the *new* moon take place near the node bringing an eclipse of the sun, the preceding or following *full* moon may be too far from the node to cause an eclipse of the moon. Under these conditions there will be only two eclipses during the year, each of the sun, and as these occur near the node, they will be central eclipses, namely, either total or annular. This has frequently happened as, for instance, in the years 1886, 1893, 1897, 1904, 1911, 1915 and 1922. By adding 18 to these dates the possibilities for the future may be manifested. If there are two solar eclipses at each node, a full moon must take place near the node and a total eclipse of the moon will result. There is thus the possibility of two partial solar and one total lunar eclipse at each node, or a total of two lunar and four solar eclipses during the year. If the node is passed about the middle of January, there may be a fifth solar eclipse within the calendar year, making a maximum of seven eclipses in a single year. There may also be three eclipses of the moon and four eclipses of the sun within the year, an event which will happen next in 1982, the three lunar eclipses each being total, and the four solar, partial. In 1935 there will be two lunar and five solar eclipses. The maximum number of eclipses falling within a calendar year is thus seven and the minimum two.

According to Oppolzer, there are 237.5 solar eclipses on the average in a century. Of these 83.8 are partial, 77.3 annular, 10.5 annular and total (the vertex of the moon's shadow just reaching the earth) and 65.9 total eclipses. Twenty-seven percent of all solar eclipses are total. On the average, therefore, two total eclipses of the sun are visible every three years, but fully half of these are inaccessible for the reason that the eclipse tracks are in high northern or southern latitudes, or pass entirely across the oceans, or lie in localities where the probability of good weather is unpromising. Consequently, on the average, about once in every three years a total eclipse somewhere on the earth is available for observation. As the duration of totality aver-

ages less than three minutes, we thus see that an eclipse observer may have an average of a minute per year for scientific work, provided he has sufficient financial backing to permit him to travel long distances for every available eclipse. Beginning in 1900, the author has witnessed four eclipses, in 1900, 1901, 1905 and 1918, each time as a member of an expedition from the United States Naval Observatory. His fifth eclipse comes this year (1923), when he will be in charge of a party from the Leander McCormick Observatory of the University of Virginia.

The Lick Observatory has set up an enviable reputation for itself in eclipse work. Through the bountiful generosity of three regents of the University of California, Colonel Fred Crocker, Mrs. Phebe Hearst and Mr. W. H. Crocker, the eclipse of 1923 makes the thirteenth eclipse witnessed by parties from this observatory, the eclipses before 1923 having been in the years 1889 (Jan. 1 and Dec. 22), 1893, 1896, 1898, 1900, 1901, 1905 (three parties in Labrador, Spain and Egypt), 1908, 1914, 1918 and 1922. In the past there have been only two failures through clouds, in 1896 and in 1914. The "dean" of eclipse observers of the present time is Dr. W. W. Campbell, director of the Lick Observatory, the 1923 eclipse being the object of his eighth expedition.

Taking into account the *earth as a whole*, it is evident that there are more solar eclipses than lunar, in the approximate ratio of four to three. But for eclipses visible from any one locality, London or New York or Timbuctoo, the question is an entirely different one. A partial solar eclipse at best may be seen from a limited portion of the globe, while a total eclipse is observable only in a very restricted path. An eclipse of the moon, being caused by its passage into the shadow of the earth, must be visible to every locality on the earth where the moon itself is visible. At any one instant of time the moon is above the horizon to half of the world, and since the eclipse of the moon, from beginning to ending of the partial eclipse, lasts for some hours it will be plainly visible to over half the globe, unless clouds interfere. There are probably very few people living who love Nature, who

have not witnessed at least one total eclipse of the moon, but probably not more than one in a thousand of the world's inhabitants has caught a glimpse of the matchless glory of the corona, seen only during the fleeting moments of a total eclipse of the sun.

Calculation of an Eclipse

The seemingly uncanny and almost miraculous power of the astronomer to predict the coming of an eclipse hundreds of years in advance has always possessed a powerful fascination for the uninitiated. By means of the Saros and of the methods outlined in the foregoing chapter, it is readily possible to foretell the happening of an eclipse of the sun or moon and the general circumstances surrounding these events, provided no very great accuracy of time or place is required. To know the *exact* times for any given locality more accurate methods must be used. The problem of eclipse calculations resolves itself into three stages. First, the accuracy of the whole problem depends mainly on the completeness of our knowledge regarding the motions of the moon furnished by the lunar theory, and also upon the motion of the earth about the sun which gives the apparent motion of the sun about the earth, the latter theory being comparatively simple. From the motions of sun and moon thus determined, it is necessary to compute their positions at equidistant intervals, and as seen from a standard place, namely, the center of the earth. Second, from these positions it is necessary to compute certain "elements" on which eclipses depend; and third, for a given latitude and longitude of any place on the earth's surface, to calculate the times, etc., of the eclipse. The first part of the problem is taken care of by various governmental publications such as the *American Ephemeris,* the British *Nautical Almanac,* the *Connaissance des Temps,* and the *Berlines Jahrbuch.* These volumes appear two or three years in advance and give the coördinates of the sun for each day at noon and those of the moon for every hour of every day. From such information it is possible by interpolation to find the exact

positions of sun and moon at any given instant of time. Elements of eclipses needed for the second step of the process have been calculated, from the earliest historic times up to the twenty-second century, by Oppolzer and by Simon Newcomb. For the computation of the circumstances of the eclipse for any given locality, two different methods are usually followed, that of Bessel or that of Hansen. The American, British and French nautical almanacs follow Bessel's method, while the German *Jahrbuch* and Oppolzer's *Canon* are based on Hansen.

The calculation of an eclipse of the moon is one of great simplicity. The time at which the moon passes into the shadow cast by the earth is the same absolute instant of time no matter where the observer is on the earth. Even the inhabitant of Mars (who may or who may not exist), who observes the earth for signs of life with the gigantic telescope which his supposed advanced civilization must have furnished him, would see the eclipse of the moon at identically the same absolute second of time as that noted by the Astronomer Royal at Greenwich. The local time of the eclipse recorded by the Martian clock would not be Greenwich mean time,— but that is not part of the problem. Eclipses of Jupiter's satellites, caused by the passing of these moons into the shadows cast by the planet are seen at the same instant of time by all observers on the earth, provided of course that the terrestrial observers are on the side of the earth turned towards Jupiter. If the various observers take the value of the Greenwich mean time of such an eclipse (which can be obtained from the nautical almanacs) and compare this with the local mean time of the individual observation, the difference in times will give the longitude of the observer from Greenwich. This is a method much in vogue for the determination of longitude when no great accuracy is necessary, for such an eclipse is a gradual phenomenon and not one which comes with great suddenness. The Greenwich mean times of the phases of an eclipse of the moon are the same for every inhabitant of the earth, and consequently, in each of the annual nautical almanacs it is possible to publish the Greenwich times of the various

portions of the eclipse, such as the beginning of the partial eclipse, the beginning of the total eclipse, etc. If the person observing the lunar eclipse lives in Western Europe, in Great Britain, France, Spain, Portugal, Holland, Belgium or any of the other countries that now keep Greenwich time as standard, the times of the eclipse will be that recorded by their clocks, if these keep correct time. If the observer lives in New York or Washington or anywhere in United States or Canada where Eastern Standard time is used, the times of the eclipse will be obtained by subtracting 5 h., 0 m., 0 s. from the Greenwich time, while if he lives in San Francisco it will be necessary to subtract 8 h. from the Greenwich time.

The method of calculating the times of a lunar eclipse, as given in the ephemerides, is a beautifully attractive problem which may be solved quite simply by anyone even though he is not an expert computer, and this may be accomplished either by graphical methods or by logarithmic calculation. Since the earth has an atmosphere, the outline of its shadow is not sharp and well-defined, but hazy when examined by a telescope. On account of the indefinite outline of the earth's shadow, its theoretical diameter must be augmented. Different computers utilize different values for this increase, varying from one-fiftieth to one-seventy-fifth of the theoretical value of the diameter of the earth's shadow. Accordingly, a total lunar eclipse is not a sudden phenomenon like an eclipse of the sun and there is, therefore, no need to employ very refined methods of computation, or to carry the calculations to fractions of a second of time. The *American Ephemeris* gives the times to the decimals of a minute, — an accuracy sufficiently great for the purpose. The method of calculating a lunar eclipse is given in Chauvenet, *Spherical and Practical Astronomy,* Vol. 1, p. 589. For graphical methods of determining the times of eclipses of moon and sun, and also of occultations, see a series of articles by Rev. W. F. Rigge in *Popular Astronomy,* volume III.

As just stated, an eclipse of the moon does not permit of an exact calculation owing to the ill-defined nature of the

earth's shadow caused by its atmosphere. Due to the refraction of light by the earth's atmosphere, the sun's light, or rather the rays at the red end of the spectrum that are not absorbed by the atmosphere, reach the moon, even at the middle of totality when the earth is directly between the moon and the sun. If the " man in the moon " were to view the phenomenon that would form, to him, an eclipse of the sun, he would see the earth surrounded by a great ring of light, its own illuminated atmosphere. If the moon had even a rare atmosphere, there would, for this same reason, be a ring of light around the moon as it encroached upon the face of the sun at the time of a solar eclipse. No such light is visible, which is a sure proof that any atmosphere the moon may possess must be rarer than can be made by the best vacuum pump ever constructed by man. The coming of totality at the time of an eclipse of the sun is a sudden phenomenon and as a consequence the approximate methods utilized in calculating a lunar eclipse are not sufficiently precise. The best method to follow in determining the times of a total eclipse is that of Chauvenet, *Spherical and Practical Astronomy,* 1, 436. Another excellent guide is Buchanan, *Theory of Eclipses.*

The calculation of a solar eclipse, in fact, cannot be treated in the simple manner of that of a lunar eclipse owing to the large size of the moon's parallax. In other words, the moon is so comparatively near the earth that it is projected on the face of the sun differently for every separate place on the earth's surface. As a result, the times of beginning and ending of the partial and total phases of the eclipse are different at every station.

The accuracy with which the times of solar eclipses can be predicted depends on the reliability of the work of the astronomers of all ages, and on the manner in which the torch has been passed on from one generation to the next. The chief cause of concern is found in the motions of our unruly neighbor, the moon. The position of the moon is furnished from observations of the times of contact of the limbs of the sun and moon, four different contacts being recognized. First contact is the instant that the moon be-

gins to creep on the face of the sun, the eclipse beginning on the western edge of the sun. Second contact is signaled by the beginning of totality, third contact by the ending of totality and fourth contact is the ending of the eclipse, the moon passing off the face of the sun, the last contact being found on its eastern edge. The four contacts are generally observed visually by a pair of field glasses or by a telescope of moderate power. The time of first contact is difficult to observe with accuracy since nothing is to be seen at the edge of the sun until the moon is actually projected on to the face of the sun, — and first contact has already actually taken place. In other words, the observer is always too late in noting the time of first contact, the amount of tardiness depending on the size of the telescope, the state of the seeing, but especially on the skill and experience of the observer, which in turn depend on the number of eclipses witnessed. Fourth contact is easier to observe than first since the moon can be followed in the telescope until it leaves the face of the sun. The beginning and ending of totality can be more accurately observed than the two other contacts, but they are subject to some uncertainties on account of irregularities in the profile of the moon at the points of contact. By means of photographs taken just before and just after totality, when the crescent of the sun is small and changing rapidly, the times of second and third contacts can be determined with much greater degree of precision than is attainable in visual work. It goes without saying that the error of the chronometer should be known as accurately as possible (probably obtained by wireless signals), that the observed times should be recorded on the chronograph, and that the latitude and longitude be known.

The photographs for contacts will unquestionably be taken with the same instrument used during totality for the corona. It will be necessary, therefore, to utilize a different method of exposure and different technique from that employed on the corona. The brilliancy of the crescent sun compared with the corona will be very great. To diminish the brightness of the crescent images it will be necessary to use a rapid exposing shutter. The best results photographically will be secured by using slow, fine-grained plates, and they should be specially "backed" to prevent halation caused by reflection from the glass side of the plate. (See Chapter VII.)

At the eclipse of 1905, totality came ahead[1] of its predicted time, the beginning of totality being 17 seconds earlier, while the ending came 23 seconds earlier than the times predicted by the *American Ephemeris.* The middle of totality was thus 20 seconds ahead of that calculated, while the duration of totality was some six seconds less than was expected from the computations. The time predicted for the middle of totality by the British *Nautical Almanac* was identical with that furnished by the *American Ephemeris* but the duration of the former was $1^s.7$ less than that of the latter, while the duration calculated from the *Connaissance des Temps* was five seconds greater than that of the *American Ephemeris.* All observers at the Spanish eclipse had their program of observation greatly interfered with by having the moon so far in advance of its predicted place. Before the eclipse of June, 1918, the observers of the U. S. Naval Observatory party in Oregon were furnished by the Washington authorities with a correction of 12.5 seconds to be applied to the times of contacts calculated from the *American Ephemeris.* The observed times were about fourteen seconds ahead of those predicted by the *Ephemeris.* At the eclipse of 1922, the Lick Observatory party observed the beginning of totality some sixteen seconds earlier than the time predicted, while the end of totality came twenty seconds earlier than the Almanac prediction.

Apparently, therefore, after having made due allowance for all known possible sources of error, the moon has strayed from the path mapped out for it by the mathematical astronomers by an amount which is not inconsiderable. What is the cause of the moon being ahead of its predicted place?

The first of the great modern authorities dealing with the

[1] *Lick Observatory Bulletin, 4,* 118, 1905.

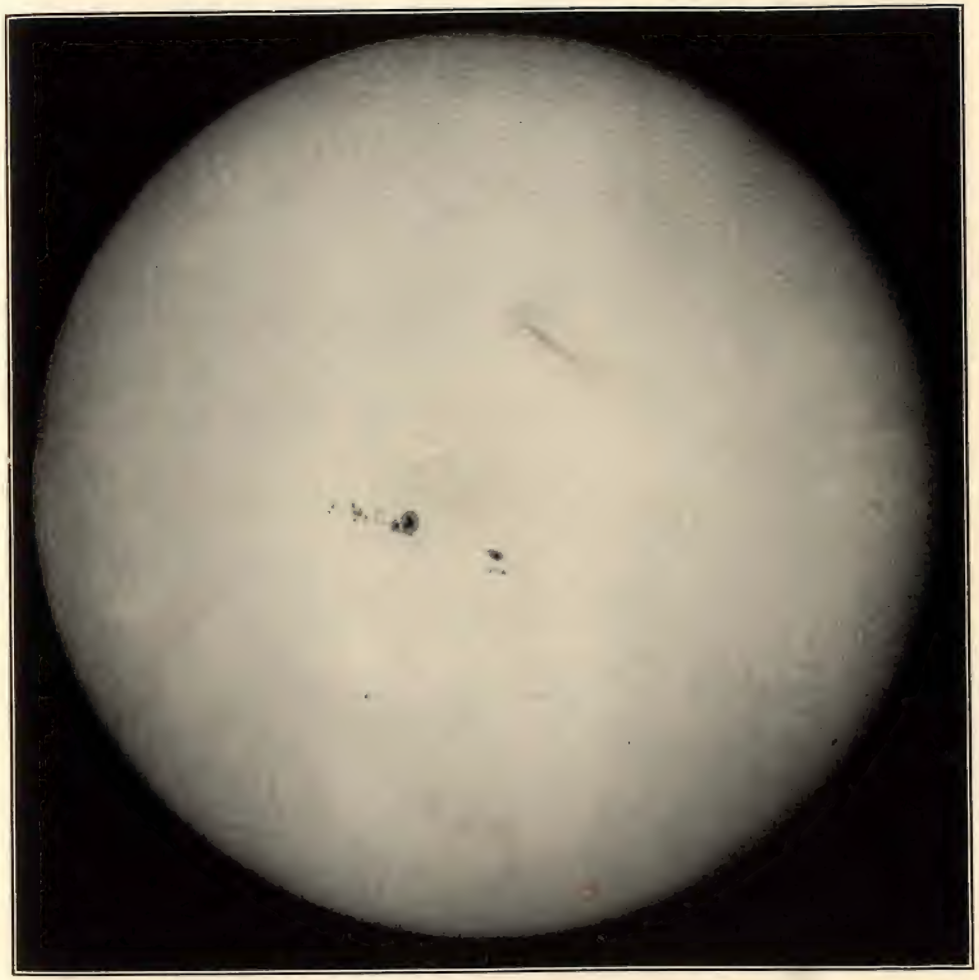
motion of the moon was Hansen, who, in 1857, published his *Tables de la Lune*. By the help of these tables the unexplained fluctuations in the moon's motion were reduced to a small fraction of their former amount. Hansen derived the inequalities in the moon's motion largely from the gravitational theory, but in order to satisfy the observations made with great care at Greenwich between 1750 and 1850, it was necessary for him to apply two empirical terms supposed to come from Venus, the larger of the two having a long period of 239 years.

The next advance was made by Simon Newcomb, who published his *Researches on the Motion of the Moon* in 1878. In addition to the observational material utilized by Hansen, Newcomb discussed all of the lunar eclipses recorded by Ptolemy in the *Almagest* and in addition a large number of mediaeval lunar eclipses. He discussed a few ancient solar eclipses, but excluded them from his calculations on account of their unreliability. The chief value of Newcomb's great work lay in collecting and discussing observations of occultations and solar eclipses in the century and a quarter previous to 1750. Newcomb had thus 250 years of observations to discuss in place of the hundred years of observations available to Hansen. The whole material was utilized to secure the value of the moon's motion and acceleration, and clearly showed the presence of an unexplained term of long period. Newcomb did not deduce the period of this term from the observations themselves but assumed it identical with one of Hansen's terms (which is now known to be faulty). "It is no small tribute to the thoroughness of Newcomb's work that while the observations from 1750 onwards have been thoroughly examined by Cowell, Radau, and Brown, the reductions of the observations from 1621 to 1747 have never been revised by anyone but Newcomb himself."[1]

The third great investigation of the lunar theory is found in E. W. Brown's *Tables of the Moon's Motion,* published in 1920. These tables are more complete than those of Hansen and Newcomb, and take account of every term of

[1] Fotheringham, *Monthly Notices, R. A. S., 80,* 289, 1920.

N



DIRECT PHOTOGRAPH OF THE SUN, MAY 18, 1910

Taken into forty-inch Yerkes refractor by Slocum. Two-thirds of original size. For enlarged photograph of spot group see p. 76.

appreciable significance. In addition to these three great monumental works on the Theory of the Moon by Hansen, Newcomb and Brown, many researches have been made by competent authorities dealing with special fluctuations and empirical terms. The chief discussions have been published by Cowell, Ross, Radau and Fotheringham in a series of papers in *Monthly Notices, R. A. S.* and in the *Astronomical Journal.*

Tables of the Moon are needed for two separate purposes; first, for predicting the place of the moon in the almanacs, so that the comparison with observations may furnish a means of further correcting the tables; and second, for the purpose of predicting eclipses with the highest degree of precision. For the first purpose it is desirable to keep the theory as free as possible from arbitrary empirical terms so that it may not be cluttered up by too many additions. For the prediction of solar eclipses, however, theory should represent observations as accurately as possible. After the exhaustive investigations by so many competent authorities, allowance having been made for the gravitational attraction of every possible cause of disturbance, it is unmistakable that the moon departs from its theoretical place in an irregular manner. If the lunar theory shows that the moon's mean longitude has an acceleration, even though a very small one, the effect of this acceleration will be cumulative. In investigating the motion of the moon, time is measured in centuries. If x is the acceleration per century (called the secular acceleration), and T the time in centuries, the effect of the acceleration will be measured by $x\,T^2$. Hence even a very minute value for x will cause a very appreciable effect provided T is large enough, or in other words, under the condition of the great time interval of the very earliest of the eclipses.

Fotheringham[1] chose eleven of the ancient solar eclipses, for the reason that the records concerning them were reliable or because they had been the subject of previous investigations, and he discussed these eclipses for the purpose of discovering a secular acceleration of the moon. The eleven eclipses selected were:

[1] *Monthly Notices, R. A. S.*, *81*, 104, 1920.

1. The eclipse of Babylon, July 31, 1063 B.C.
2. The eponym canon eclipse, June 15, 763 B.C.
3. The eclipse of Archilochus, April 6, 648 B.C.
4. The eclipse of Thales, May 28, 585 B.C.
5. The eclipse of Pindar, April 30, 463 B.C.
6. The eclipse of Thucydides, August 3, 431 B.C.
7. The eclipse of Agathocles, August 15, 310 B.C.
8. The eclipse of Hipparchus, Nov. 20, 129 B.C.
9. The eclipse of Phlegon, November 24, 29 A.D.
10. The eclipse of Plutarch, March 20, 71 A.D.
11. The eclipse of Theon, June 16, 364 A.D.

A thoroughly excellent discussion shows that all classes of ancient observations, including the eleven solar eclipses above, are adequately satisfied by assuming an acceleration of the moon $10''.8$ per century. In addition, an acceleration was found for the sun amounting to $1''.5$ per century.

Part of these variations can be accounted for by irregularities of our time-keeper, old Mother Earth, fluctuating as she revolves on her axis. Both Glaubert[1] and Ross[2] seem to find unmistakable evidence that the earth's period of rotation is changing slowly, for the longitudes of the moon, the longitudes of the sun, the longitudes of Mercury, Venus and Mars exhibit irregularities which are very similar, the curves resembling each other very closely. The Washington, Paris and Greenwich observations, according to the discussion by Ross, appear to show that a marked change in the sun's acceleration began in the year 1898.

The apparent cause of the secular solar acceleration of $1''.5$ and the secular lunar acceleration of $10''.8$ seems, according to Taylor and Jeffreys,[3] to be found in the friction of the ocean tides, especially those where there are long bays and channels and where there is a large rise and fall of water. Such basins are found in the English Channel, the Irish Sea, Bay of Fundy, Behring Strait, etc. The tides known to exist in the mass of the earth itself appear to have little effect. The tidal friction of the land-locked and shallow seas causes a direct acceleration of the moon's orbital motion as well as a spurious acceleration

[1] *Monthly Notices, R. A. S., 75,* 489, 1915.
[2] *Astronomical Journal, 29,* 152, 1916.
[3] *Monthly Notices, R. A. S. 80,* 308, 309, 1920.

through the increase in the length of the standard of time.

Modern observations up to 1890 are little affected by the empirical terms, but in the coming years of the twentieth century the values will increase as shown by the quantities given below by Brown[1] for various years:

1750	$-0''.02$	1875	$-0''.21$
1775	$+\ .24$	1900	$+1\ .48$
1800	$+\ .09$	1925	$+4\ .65$
1825	$-\ .18$	1950	$+9\ .42$
1850	$-\ .57$		

What a perfect science astronomy is! An observation of an eclipse of the sun made three thousand years ago at the dawn of human civilization has an important bearing on the most recent refined researches on the motion of the moon!

[1] *Astronomical Journal, 29,* 152, 1916.

CHAPTER V

THE SPECTROSCOPE

ASTROPHYSICS, called the "new astronomy," has revealed in a remarkable manner through its discoveries during the past half century the wonderful ability and resourcefulness of the human brain, making it evident that man is gifted with almost infinite powers. From this earth of ours, which astronomy teaches us to be but an insignificant speck among the countless orbs of the universe, man has been able to reach out and ascertain the physical constitution of the sun, and to acquire this information with almost the certainty of a chemist who could make a qualitative analysis provided that an average specimen of the sun's matter could be furnished him. And across millions and millions of miles of space, the far distant suns, the stars, shining by their own feeble light, are made to give up the secrets of their construction. Not only can we learn of the constitution of the sun and stars, but we can also ascertain their effective temperatures as well, and with information thus garnered we can arrange the stars in an orderly sequence, tracing their evolution from the swollen red stars of very minute density, the so-called "giants," through the successive stages of yellow and white to that of the stars of class B, and then on in the descending branch of development as the stars become cooler and more dense. The astronomer believes in evolution and recent researches make evident that our gigantic sun is but a yellow "dwarf," well advanced towards the state of old age and final obscurity. It is by means of the spectroscope that such information is gathered, and by the spectroscope it has become possible to investigate motions, not athwart the sky as the older astronomy was able to do, but towards us or away from us in the line of sight, and to measure these motions in miles per second. The shift

of the lines of the spectrum due to motion in the line of sight, which has been confirmed experimentally in the laboratory, has given rise to many interesting developments in astrophysics: the discovery of an entirely new class of bodies, spectroscopic binaries, the measurement of the axial rotation of the sun and Jupiter, as well as providing a magnificent confirmation of the meteoric constitution of Saturn's rings. And quite recently the greatest triumph of the spectroscope has been achieved by Adams and his co-workers at Mount Wilson Observatory being able to determine the distances of the stars and thus find their luminosities compared with that of the sun. Since its birth in 1859, when Kirchhoff discovered the principles of spectrum analysis, astrophysics has advanced by leaps and bounds. In no branch of astronomy has the new instrument of research shown its outstanding value quite as clearly as in the development of the subject of eclipses of the sun. For a clear understanding of the matter it will therefore be necessary to give a brief account of the history of the new astronomy.

The scientific world owes much to John Kepler for handing down to us the three great laws of planetary motion, but his activities extended beyond the realm of mathematical astronomy into the domain of physics. He was the first to show — as he did in his "Dioptrics" — that if a beam of sunlight be allowed to fall upon a prism in a certain way it passes out as a colored beam, giving the colors of the rainbow. And as the great Sir Isaac Newton took Kepler's Laws and used them for finding the law of gravitation, so likewise he extended the physical work of Kepler and by reason and experimentation greatly increased our knowledge. In fact, it is from Newton's labors that the science of spectrum analysis virtually had its birth.

In 1666, Newton, by allowing sunlight to pass through a hole in a shutter and to fall on a glass prism, found a colored ribbon of light, an impure spectrum. His description of the effect observed is so clear that the following is copied from *Optics*, Third edition, page 21.[1]

[1] See also, *The Spectroscope and its Work*, Newall, 1911. For greater details consult *Chemistry of the Sun*, Lockyer, 1887, and *Handbuch der Spectroscopie*, Kayser, Vol. 1.

"In a very dark chamber at a round hole about one-third part of an inch broad made in the shut of a window I placed a glass prism, whereby the beam of the sun's light which came in at that hole might be refracted upwards toward the opposite wall of the chamber, and there form a colour'd Image of the Sun. The axis of the prism (that is the line passing through the middle of the prism from one end of it to the other end parallel to the edge of the refracting angle) was in this and the following experiments perpendicular to the incident rays. About this axis I turned the prism slowly, and saw the refracted light on the wall or coloured image of the sun first to descend, and then to ascend. Between the descent and ascent when the image seemed stationary, I stopped the prism and fix'd it in that posture, that it should be moved no more. For in that posture the refractions of the light at the two sides of the refracting angle, that is at the entrance of it, were equal to one another. So also in other experiments, as often as I would have the refractions on both sides of the prism to be equal to one another, I noted the place where the image of the sun formed by the refracted light stood still between its two contrary motions, in the common period of its progress and regress; and when the image fell upon that place, I made fast the prism. And in this posture, as the most convenient, it is to be understood that all the prisms are placed in the following experiments, unless where some other posture is described. The prism therefore being placed in this posture, I let the refracted light fall perpendicularly upon a sheet of white paper at the opposite wall of the chamber, and observed the figure and dimensions of the solar image formed on the paper by the light. This image was oblong and not oval, but terminated with two rectilinear and parallel sides, and two semicircular ends. On its sides it was bounded pretty distinctly, but on its ends very confusedly and indistinctly, the light there decaying and vanishing by degrees."

Newton concluded that white light was made up of separate colored rays; by passing the light through the prism, the different rays suffered different amounts of refraction; they were in fact dispersed, and as a result the spectrum consisted of an infinite number of colored images of the round hole lying side by side In the middle of the spectrum the different rays overlapped, and white light resulted, but the ends remained colored. Newton found that by the use of a slit "an inch or two long, and a tenth or a twentieth of an inch in width," the spectrum became purer; and he even tried a triangular hole, observing greater and greater purity as the vertex was approached. He proved conclusively that the colors came from the sun's light itself and not from the prisms, for he produced spectra with a variety of different prisms, and afterwards combined the prismatic colors together to make white light. He further showed that each ray of light consisted of a single color and possessed a certain definite refrangibility.

Newton's books on optics (published in 1704) are marvels of clearness of exposition, and his fundamental experiments have come down to us almost unchanged. The significant result of Newton's work is that the pure colors, and not white light, occupy the primordial position of importance, since it is possible to form all conceivable colors including white light from a mixture of the pure colors. A determined color in the spectrum is defined through its index of refraction, and since this quantity continually varies, there is an infinite number of spectral colors.

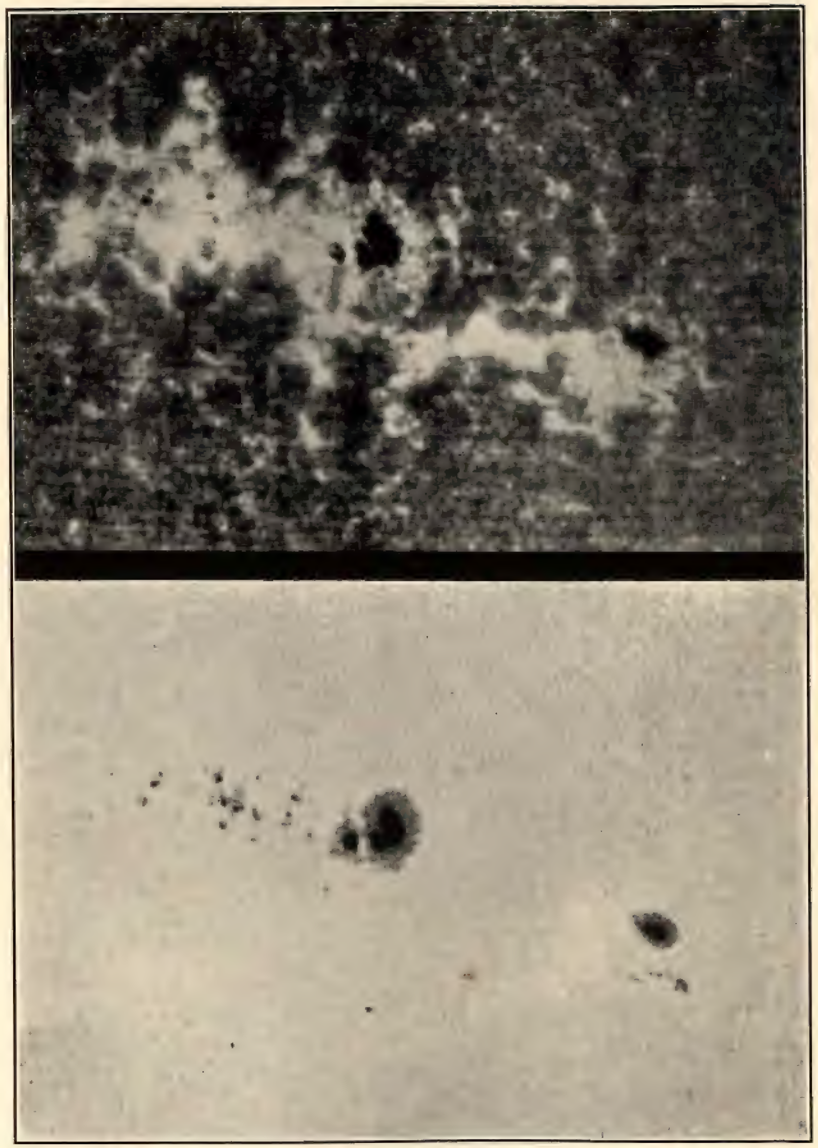
Newton did not see any of the dark lines of the solar spectrum, now known as Fraunhofer lines, though he used a narrow slit and should have been able to see them, — but his prisms were poor (as he himself said). The authority of his great name discouraged further experimentation, and no advances were made for one hundred years. Unfortunately he made some mistakes, first in dividing the colors into seven, the quantitative number of such great attraction and "perfection" to the early scientists, thereby perhaps preventing the discovery of the Fraunhofer lines, and second, in not seeing that various media dispersed differently. As is well known, Newton said that the case of the refracting telescope was a deplorable one, and following his time these telescopes were made of enormous lengths,

up to two hundred or even three hundred feet, in order to minimize the color difficulty. However, if Newton had been in a position to make use of different kinds of glass of crown and flint as Fraunhofer was later, it is altogether likely that many other discoveries of great importance would have been made by him.

The long period of arrested progress was broken in 1802 when Wollaston, making use of a slit, repeated Newton's experiments. He then found,[1] "The colours into which a beam of white light is separated by refraction appears to me to be neither seven, as they are usually seen in the rainbow, nor reducible by any means to three, as some persons have conceived; but that, by employing a very narrow pencil of light, four primary divisions of the prismatic spectrum may be seen with a degree of distinctness that, I believe, has not been described nor observed before. . . . The four colors are, red, yellowish-green, blue and violet." He then goes on to describe the dark markings that were seen in his spectrum, these being ill-defined in appearance and evidently taken as the natural divisions between the colors. It is readily apparent that the prisms used by Wollaston were likewise poor in quality, for his experiments were made in a manner that should have brought to view the thousands of dark lines in the solar spectrum. However, a very great advance was made over the work of Newton, for the spectrum of a candle flame and of an electric light were examined. Spectra were found which not only differed from each other in appearance but each of which was entirely unlike that furnished by the sun. The candle and the electric light each gave a spectrum of bright lines, a discontinuous spectrum. The fundamental importance of these experiments was not at the time recognized.

The life of Joseph Fraunhofer[2] had an almost tragic beginning. At the age of fourteen he lived in a dilapidated house in an alley in Munich which tumbled down and buried its occupants in the ruins. The other residents were

[1] *Phil. Trans.*, part 1, 378, 1802.
[2] Clerke, *History of Astronomy during the Nineteenth Century.*



SUN-SPOTS ON MAY 18, 1910

Photographed by Slocum with Yerkes refractor. *Above:* Spectroheliogram with Calcium H_2. *Below:* Direct Photograph.

killed, but the boy, who was an orphan, was dragged out, more dead than alive and seriously injured. The Elector Maximilian Joseph was a witness of the accident and to show his commiseration made him a present of eighteen ducats. Besides the purchase of books and of a glass-grinding machine the money permitted his release from apprenticeship to a looking-glass maker. Through study and toil and privation he increased his knowledge of the optician's art and at the age of nineteen entered the glass-making firm of Von Reichenbach and Utzschneider. He devoted himself now with great avidity to a study of lenses for the purpose of improving the refracting telescope. After Newton's time, Dollond had discovered that it was possible to banish most of the color which so interfered with the action of the refracting telescope, by combining a lens of crown glass with one of flint. By means of many experiments with prisms of glass of different varieties, Fraunhofer was able to investigate the best combination of two lenses that would give the most perfect definition with freedom from the disturbing color. In 1817 there was finished the great "Dorpat refractor" with the then unprecedented aperture of nine and a half inches. This telescope in the skillful hands of Struve became one of the most famous telescopes ever in existence. To Fraunhofer the astronomical world is also indebted for the first really serviceable heliometer, that at Königsberg, an instrument which was to play an important part in extending our knowledge of the sidereal universe by permitting the measurement of stellar distances, or, as they are technically called, stellar parallaxes.

In 1814, Fraunhofer not only extended Wollaston's work but introduced great improvements in the method of observing. The slit was retained but placed at a great distance from the prism. Instead of allowing the refracted beam of light to fall on a screen he placed a small telescope directly behind the prism and by this means a magnified view of the spectrum was obtained.

"Into a dark room, and through a vertical aperture in the window-shutter, about 15″ broad and 36″ high, I intro-

duced the rays of the sun upon a prism of flint glass placed upon the theodolite; this instrument was 24 feet from the window, and the angle of the prism was nearly 60°. The prism was placed before the object glass of the telescope, so that the angles of incidence and emergence were equal. In looking at this spectrum for the bright line which I had found in the spectrum of the artificial light, I discovered, instead of this line an infinite number of vertical lines of different thickness. These lines are darker than the rest of the spectrum, and some of them appear entirely black."[1]

The interrelation of these lines and streaks appears to be the same no matter what refracting substance is employed so that, for instance, a particular band is found in each case only in the blue, another is found only in the red, and one can therefore learn to recognize a particular line in the spectrum by noting its position with respect to the prominent lines. Fraunhofer observed that the strong lines did not mark the edges of the colors as Wollaston had supposed and further that the same color is found on both sides of the line, the colors grading by imperceptible degrees from one color to the next. Starting from the violet end of the spectrum, the colors are given the following names: violet, indigo, blue, green, yellow, orange and red. As Lockyer has pointed out, the first letters of these color names make the combination VIBGYOR, — an aid to memory that the beginner may find useful.

Fraunhofer constructed a map of the lines of the solar spectrum, measuring by means of the circle of the theodolite the accurate positions of over 350 lines, though he counted no less than 754. Starting at the red end of the spectrum he called the more prominent lines by the letters of the alphabet. Thus A, B and C denote lines in the red part of the spectrum, D the prominent double lines in the yellow part, which we now know to be due to sodium, while H and K in the violet are the very broad lines caused by calcium. In addition, the small letters of the alphabet were made use of, *b*, for instance, denoting a group of lines in the green due to the element magnesium. Not only are the

[1] *Denkschriften der K. Akad. der Wissen. zu München, 5,* 193, 1814.

prominent lines of the solar spectrum to which Fraunhofer gave names called after their discoverer, but all dark lines in the spectrum whether prominent or faint are known as Fraunhofer lines.

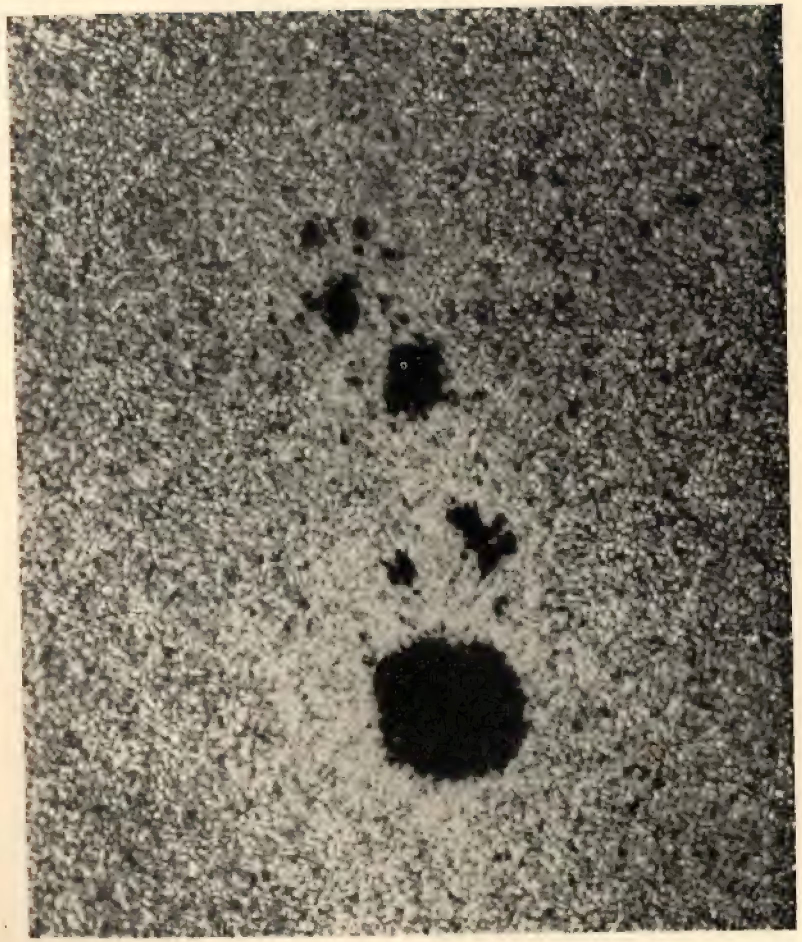
He plotted his lines not according to their wave-lengths as in the manner of all modern maps, but according to a rather arbitrary scale. Now that the solar spectrum has been more fully investigated with the perfected apparatus of the twentieth century, we can go back and gauge at its true value the worth of Fraunhofer's map. Thus we have the opinion of Hartmann of Potsdam to the effect that Fraunhofer made his map with the greatest degree of refinement and secured a precision which has warranted spectroscopists of the past hundred years placing in it the great confidence that they have felt. Fraunhofer's life and work is a splendid example of what one man by patient and careful work can accomplish for the cause of science. Any one who has ever looked into a spectroscope will realize what a colossal work the making of this map must have been.

Since the lines and bands in the color image have only a very small width, it is evident that the apparatus must be most perfect to avoid all aberrations which could either render the lines indistinct or entirely scatter them. The faces of the prism must therefore be perfectly plane; the glass to be used in such prisms should be entirely free from waves, streaks and striae; and the greatest care should be exercised in their grinding and polishing. These and other considerations, such as, that the slit must be parallel to the edge of the prism, Fraunhofer found out by careful experimenting.

Fraunhofer, however, was not content with this work. He wanted to know something of the origin of the lines, and he soon came to a conclusion on this point. It occurred to him that they might possibly be attributed to some illusion caused by the narrow aperture through which the light was admitted. We know that the shape of the slit has something to do with the forms of these dark spaces in the spectrum, but with their simple existence as spaces the slit has nothing to do, the mere shape of the lines being quite a trivial matter. To settle this question beyond doubt he

changed the slit which he was using in order to ascertain if this would change his spectrum. He passed light through a small round hole of 15″ in diameter, and allowed it to fall upon the prism placed in front of the objective of the theodolite. It is clear that the color-image seen with the telescope can have only an inappreciable width, and therefore will form only a line; but in this narrow colored width no fine cross lines can be seen. In order to widen this narrow stretch of light into a band wide enough to see, Fraunhofer made use of a cylindrical lens, or a lens which is plane on one side and curved on the other resembling a portion of a cylinder of large diameter. The axis of the cylinder was placed parallel to the base of the prism and hence parallel to the line of light. Consequently, the width of the spectrum would be changed without in any way altering its length. With this arrangement the lines were observed to be exactly the same as when the light comes through a long narrow opening. Hence the bands and lines in the solar spectrum are not caused by diffraction and interference by the light passing through the slit, nor are they produced by any peculiarities in the apparatus. There is, therefore, only one other possible cause for these lines, and that is that they somehow or other belong to the light given out by the sun. Hence the solar spectrum is not a continuous spectrum having light of all colors and all wave-lengths, but is, on the contrary, a discontinuous one in which vibrations of certain lengths are missing from the sum-total which goes to make up white light.

If the sun is remarkable for this discontinuous spectrum, what types of spectra do the other heavenly bodies show? If Fraunhofer could examine the light from a small round opening at a short distance from his instrument, there is no reason, if the light were sufficient, why he should not examine the light from a round body made apparently small by the fact of its situation at a great distance. He examined, therefore, the light from Venus directly *without making the light pass through a small opening,* and he found, after spreading out the light by means of the cylindrical lens, that the same lines appeared in the light of Venus as



Sun-spot Group
Photographed by Janssen at Mendon, April 1, 1894.

appear in sunlight. Since, however, the light from the planet is very feeble in comparison with the light received from the sun, the intensity of the violet and red colors of its spectrum are very weak, and on this account even the stronger lines in both these colors are seen with difficulty, though in the other colors they are very easily distinguished. Fraunhofer was able to see D, E, *b* and F perfectly defined and he even recognized in the triplet *b* in the green, two lines, one weak and one strong, although he was unable to see that the stronger of these two lines was really a double line. This, of course, was due to the weakness of the spectrum, and for this same reason the other finer lines could not be distinguished satisfactorily. By measuring the arcs DE and EF it was made certain that the light from Venus contained, as far as could be analyzed, just the same lines in its spectrum as did the light of the sun.

With this same apparatus observations were made on the light of some fixed stars of first magnitude, but since the light of these stars is much weaker than that of Venus, it is natural that the brightness of the spectrum should be much less. In spite, however, of this comparative lack of brilliancy, Fraunhofer was able to recognize with certainty in the spectrum of Sirius three broad lines which appear to have no connection with those of sunlight: one of these is in the red, one in the green, and the other in the blue. In the spectra of other fixed stars of the first magnitude, lines were actually recognized by him, and it seemed certain that these spectra though very faint differed amongst themselves. The observations were made with a telescope of an aperture of about one inch, so that it was impossible for the distinguished pioneer to do more than to point out the way. In such a manner as this was the science of stellar spectroscopy born.

As we have seen, Fraunhofer examined the stellar spectra by allowing the light from the star to fall directly on the prism and after refraction to examine this light by the telescope. This same method of observation is still of the greatest scientific value and it is in this way that Harvard College Observatory has been able to accomplish such an

enormous amount of sound research by methods involving the use of the spectroscope. The combination of prism and object glass is called an "objective prism" — or, when used for photographing, the "prismatic camera." If we point such an instrument to any place in the sky, we can view by our eye, or photograph on a plate, the spectrum not of one star only, but of all the stars that are in the field of the telescope.

It is not to be wondered at that a man who had thus brought sun, planet and star within the grasp of a new instrument should not rest content with these observations.

Fraunhofer next investigated at considerable length the spectra of artificial light. In an early part of his paper he states that, on examining the spectra of flames, he found that flames such as that of a lamp and candle, and, indeed, in general the light produced by the flame of a fire, exhibit between the red and yellow of the spectrum a clear and well marked line which occupies the same place in all the spectra. Returning to this subject later, he notes that in transmitting the light of a lamp through the same aperture employed for the examination of the solar spectrum, a line appears which corresponds exactly to the position of the D line in the solar spectrum. In fact, the resemblance to the solar D line is so close that both the bright artificial line and the solar D line are each a fine double line. This was the first step towards the true explanation of the dark lines in the solar spectrum; but it took many years before the true meaning was arrived at, mainly on account of the presence of this bright D pair in practically every flame and under all conceivable sets of conditions.

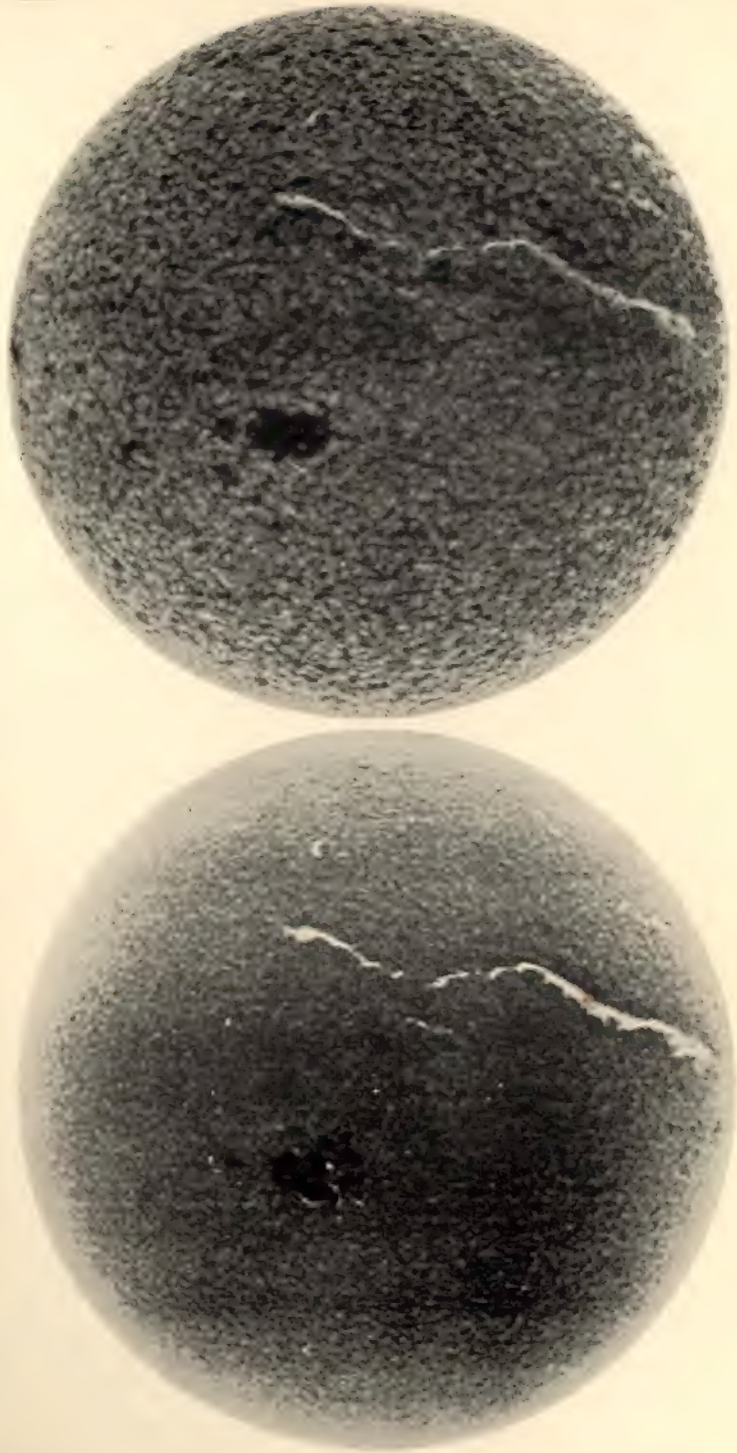
According to Agnes M. Clerke,[1] "the ubiquity and conspicuousness of the sodium-line long impeded progress. It was elicited by the combustion of a surprising variety of substances — sulphur, alcohol, ivory, wood, paper; its persistent visibility suggesting the accomplishment of some universal process of nature rather than the presence of one individual kind of matter. But if spectrum analysis was to exist as a science at all, it could only be by attaining certainty as to the unvarying association of one special substance with each special quality of light. It appeared, indeed, without fail where sodium *was;* but it also appeared where it might be thought only reasonable to conclude that sodium *was not*. Nor was it until thirty years later that William Swan, by pointing out the extreme delicacy of the spectral test, and the singularly wide dispersion of sodium, made it appear probable (but even then only probable) that the questionable yellow line was really due invariably to that substance. Common salt (chloride of sodium) is, in fact, the most diffusive of solids. It floats in the air; it flows with water; every grain of dust has its attendant particle; its absolute exclusion approaches the impossible. And withal the light that it gives in burning is so intense and concentrated, that if a single grain be divided into 180 million parts, and one alone of such inconceivably minute fragments be present in a source of light, the spectroscope will show unmistakably its characteristic beam."

[1] *History of Astronomy during the Nineteenth Century.*

The advance made by Fraunhofer in studying the refraction of light through prisms placed the new science on a very firm foundation. This remarkable progress, due to the very marked improvement in the quality of the glass used in the prisms, was rendered possible only by the employment of a telescope of greatly increased defining power. The utilization of the telescope permitted advances in the study of diffraction of light through a narrow aperture or slit, as important and as epoch-making as the investigations concerning the refraction of light. The instrument used by Fraunhofer was essentially a twelve-inch repeating theodolite whose verniers read to 4″. In the middle of the circle and about it there is a plane horizontal disk six inches in diameter which turns on its axis, and whose center lies exactly on the axis of the theodolite. On this disk, the slit to be investigated was placed. The width of the opening in the slit was measured by a micrometer devised for the purpose which could read to 0.0001 inches. Light passing through a narrow opening at the heliostat and falling on the screen with its slit is examined by the theodolite telescope. Fraunhofer discovered the diffraction pattern which consists

of a bright strip in the center having symmetrically on each side a series of bright and dark bands, if the incident light is monochromatic. If the incident light is sunlight, instead of having bright and dark bands, there will be found a series of colored bands in which, however, the transitions from one color to another are not sharply defined. The series of bands gradually decrease in brightness in passing outwards from the central beam of light until they are finally rendered invisible. Instead of employing a long, narrow opening at the heliostat, he used a small circular opening, in front of which he placed a cylindrical lens and as a result obtained bands identical with those produced by the other method.

In the process of development of this subject, the natural course after trying diffraction through a single opening, would be to try the action of two, three and more parallel openings. This was exactly the plan followed by Fraunhofer. In order to study the diffraction through a great number of openings he stretched upon a rectangular frame a great many wires of the same thickness, parallel to each other and at the same distance apart. The light was then diffracted through the intervening spaces. In order to be sure that the wires were exactly parallel and at exactly equal distances apart, he made two very good micrometer-screws, and putting these on opposite sides of a frame, he wound on this frame very fine wire, being careful to stretch the wire at a constant tension. If now he soldered along the length of the screws, each wire was thus securely fastened, and by sawing each screw in halves, two similar wire gratings were obtained. By this method gratings were manufactured consisting of wires 0.002 inches thick, and separated by spaces of 0.004 inches. Using a grating of 260 turns of wire, and examining the light which first passed through a narrow opening at the heliostat and then fell on the grating placed in front of the theodolite objective, he found, much to his surprise, phenomena which were entirely different from those observed with a single opening. The aperture at the heliostat was seen exactly as if no grating intervened, but on both sides were seen a series of spectra as perfect as he had hitherto obtained with a good prism.



THE SUN

Photographed in the light of glowing Calcium, K3 (above) and Hydrogen Hα (below). Deslandres July 22, 1922. Note the curious stretch of heated vapor in both photographs.

The series of spectra gradually increased in length but decreased in intensity, and with his apparatus he was able to count thirteen spectra on both sides of the middle. In order to vary the conditions as much as possible, gratings were made of different thickness of wire and with different spaces. Wire was wound on a screw having as many as 343 threads to the inch. Gratings were also made by scratching parallel lines on a piece of glass covered with goldfoil, through which spectra were observed exactly similar to those observed with wire gratings. Fraunhofer quickly found that the size of the spectra produced did not depend upon the width of the spaces nor upon the thickness of the wires, but upon the sum of these two quantities, or the distance apart of the centers of the wires. Consequently, the finer the screw in whose grooves the wires were stretched, the longer would be the spectra, and it became immaterial of what thickness the wire was or how wide the opening. The quality and accuracy of a grating depends on the precision attained in the attempt to arrange wires of the same width throughout, and in making the wires perfectly parallel, with their centers equally distant.

Although the same dark lines were seen in the spectrum of sunlight when produced by the grating as were found when a prism was employed, one point of difference was revealed in the relative distances apart of the lines in the two spectra. In the diffraction spectrum of the grating, each of the different colors, the red, orange and so on through the blue and violet, is about equal in extent, while in the prismatic spectrum on the other hand the colors at the red end grow more and more crowded together, with the result that the violet reaches to a much greater extent in prismatic spectra than the red. Consequently, the appearance of a diffraction spectrum differs very much from that of a prismatic spectrum, and it is well to be familiar with the two different types of spectra.

In a normal spectrum produced by a grating, the dispersion from the C line in the red to the D lines in the orange is approximately twice the distance from G to the H-line in the violet; whereas with a flint prism of 27° angle the ex-

tents of the red and violet are changed in such a remarkable manner that the distance from C to D is only one-half that from G to H.

There is also another marked difference between prismatic and diffraction spectra. In using a prism to form a spectrum, the red rays are the least bent from their incident direction, and as a result we speak of the red as the least refrangible. How is it with the diffraction spectrum with the bright beam in the center and spectra on both sides? Is the violet or the red end towards the bright patch? The red is the least refrangible end in prismatic spectra, but not in diffraction spectra, for the violet is nearest to the bright patch with the red end bent more from the original direction. However, since spectrum analysis was first developed from the use of prisms, a nomenclature has been adopted which, though applying essentially only to prismatic spectra, is used indiscriminately in respect to spectra of both kinds. Thus in referring to the least refrangible rays, the red end of the spectrum is always meant and never the violet, although in the diffraction spectrum the violet is the least refrangible end.

After measuring the angles by means of the theodolite, Fraunhofer was able to formulate two laws: first, the size of the spectra, and their distances from the center (or the dispersion) vary inversely as the distance between the centers of the lines in the grating; and second, the dispersions in the different spectra for any ray form an arithmetical series.

This second law states in other words that the angle of deflection of the same colored beams in the series of spectra formed by the grating are in the ratio of the numbers 1, 2, 3, etc. The experiments from which these results were deduced gave, however, such small angles that the sine, the tangent and the arc do not sensibly differ. If the angles were larger, that is, if the gratings had greater dispersion, it might be possible to determine whether it was the arcs themselves that form an arithmetical series, or some function of these angles. Having this in view, Fraunhofer made further experiments on gratings to find whether it would not

be possible to get gratings of greater dispersion. As it was almost impossible to evolve a screw, for the manufacture of his wire gratings, with a smaller pitch than the one he had already employed of 343 threads to the inch, he constructed a machine for scratching parallel lines upon a piece of plane glass covered with gold-foil, and he succeeded in scratching them so closely together that he was able to rule a grating with about 900 lines per inch. If more lines than this were scratched, practically no gold-foil remained. With this grating and with others, he measured the deflection for different rays in different orders of spectra and he found that the sines of the angles of deflection increased uniformly in the different orders of spectra, or in other words $Sin\ \theta = \frac{n\lambda}{\omega}$, where θ is the angle of deflection, n is the order of spectrum, λ is the wave-length and ω the grating space.

Using this equation, Fraunhofer was able to astonish the world by telling them that he had been able to measure the infinitesimal length of a light-wave, for the D line of 0.00005888 cm., which is very close to modern determinations.

To sum up the work of Fraunhofer: he was a telescope maker, and in order to improve his lenses entered into an investigation of prisms in order to study the action of light in passing through them. Using a telescope in connection with his apparatus, he found the spectrum of sunlight filled with lines, now called "Fraunhofer lines." Investigating the spectra of flames he found the bright D line doubled and in the same position exactly as the dark D in the solar spectrum. He examined the spectra of planets and stars. Taking up diffraction, he studied the action of light passing through a single opening, and formulated the laws governing it. He then studied the action of light through parallel openings side by side. Next he attempted to rule lines in a layer of grease spread over a glass plate so thinly that the film could scarcely be recognized by the eye alone. In this grease parallel lines were scratched which were only half as far apart as the lines ruled in gold-foil. After many experiments it was found impossible to rule lines in any layer of

grease or varnish much finer than the gold-foil grating. A diamond point is the only method yet known in modern engineering that will provide sharp and sufficiently clean cut lines to permit the construction of finer gratings.

Let us stop a moment and think what it means to rule a grating with a diamond and try to visualize the total lengths of the lines the diamond point must trace, practically without variation. The finest gratings ruled by Rowland have 20,000 lines per inch, and if the grating possesses a ruled surface of 3 x 6 inches, the diamond evidently rules 3 x 6 x 20,000 or 360,000 inches, a distance of nearly six miles. If in ruling this distance the diamond point wears appreciably or breaks down, the previous rulings are useless. Altogether it takes from five to six days continuous working to rule such a grating. What a task Fraunhofer must have had in ruling his gratings! Indeed it must have consumed an enormous amount of time and patience, with numerous vexations caused by imperfect rulings and the fracture of the diamond points. It was only after many trials that he succeeded finally in getting a grating with about 7500 lines to the inch. In order to obtain good definition with his little telescope it was necessary for the slit to be at some considerable distance (as much as 642 feet in one set of experiments) in front of the prism. A great advance in instrumental equipment was later made by Simms, of the celebrated optical firm of Troughton and Simms, who rendered, by the introduction of a lens between slit and prism, the incident rays parallel in falling on the prism. Thus was introduced the collimating lens which increased the compactness of the spectroscope and rendered it almost as we now use it.

In England, Brewster and Herschel undertook a great variety of experiments by means of which they examined the absorbing effects of various colored substances. A piece of red glass permits only the red part of the spectrum to pass through it, the balance of the spectrum being absorbed by the glass, while blue glass allows only the blue end of the spectrum to pass unobstructed. It consequently became evident that the absorbing effect of the terrestrial atmosphere should be carefully investigated before any certain information could be obtained regarding the cause of the dark lines in the solar spectrum. The water vapor in our atmosphere exerts a powerful absorbing action on the light of the sun as it passes through the air on its way to reach the slit of the spectroscope. The absorption commences at the blue end of the spectrum and becomes gradually greater and greater as the sun sinks towards the horizon. For very dense layers of atmosphere, when the sun is near the horizon either in rising or setting, the absorbent action is so great that little of the solar spectrum penetrates except the yellow and red parts, the violet end being entirely absorbed. For this reason the sun is always red when rising or setting, and the color becomes a deeper red when dust or haze in the atmosphere causes a greater absorbing effect. At the time of a total eclipse of the moon, the light from the sun passes through what might be termed a double layer of terrestrial atmosphere with the consequence that there is an increased absorption, the moon thus shining with a dull copper colored hue, and this in spite of the fact that the moon is immersed in the shadow cast by the earth!

By 1833, Brewster announced that he had examined the lines of the solar spectrum with various optical combinations, and had made a map of the solar spectrum on a scale four times that of Fraunhofer. Indeed for some portions of the spectrum the scale was twelve times Fraunhofer's. By observing the absorbing effect of various substances he soon found that some of these substances exerted a general darkening action on the spectrum, whereas other materials produced an absorption in a limited portion of the spectrum. At times the effect was so limited in action that bands or even lines, sharp and distinct, were added to the solar spectrum. These phenomena were so clearly defined that the conviction was borne in upon Brewster that he had obtained "the discovery of a general principle of chemical analysis, in which simple or compound bodies might be characterized by their action on definite parts of the spectrum."

In the course of his investigations, Fraunhofer varied the conditions under which he observed, using different kinds

of slits to see if the dark lines in the solar spectrum were caused by some action at the slit itself; but when he found that the form of the slit had nothing to do with the presence of the lines, he concluded that the lines must be truly solar in their origin. Brewster endorsed this view and inferred that if a tube of nitrous oxide gas gave lines identical in character with the solar lines, these lines must then be caused by absorption at the surface of the sun. When in addition he found that many of the lines of nitrous acid gas appeared to be identical in position with some of the Fraunhofer lines, the verification seemed to be complete. Brewster made another important discovery which is described in his own words as follows: "When the sun descends towards the horizon and shines through a rapidly increasing depth of air, certain lines which before were little, if at all, visible, become black and well defined, and dark lines appear even in what were formerly the most luminous parts of the spectrum." As these lines appear both at sunrise and sunset, Brewster announced the discovery that these bands and lines were caused by the absorbent effect of the earth's atmosphere. Since the majority of the lines in the sun, however, appeared without change, he concluded that, "the apparent body of the sun is not a flame in the ordinary sense of the word, but a solid body or coating raised by intense heat to a state of brilliant incandescence."

To quote from Lockyer, *Chemistry of the Sun*, page 41, "It will be seen, then, that the study of the sun was now (1833) in full swing. We had at length, after waiting some centuries, a method of observing a spectrum; we had, further, the fact that there were dark lines in the solar spectrum; that colored flames gave us bright lines; that certain substances stopped some of the light which passed through them, thus producing dark lines. Hence that the solar lines might be produced in the same way."

CHAPTER VI

THE SPECTROSCOPE (CONTINUED)

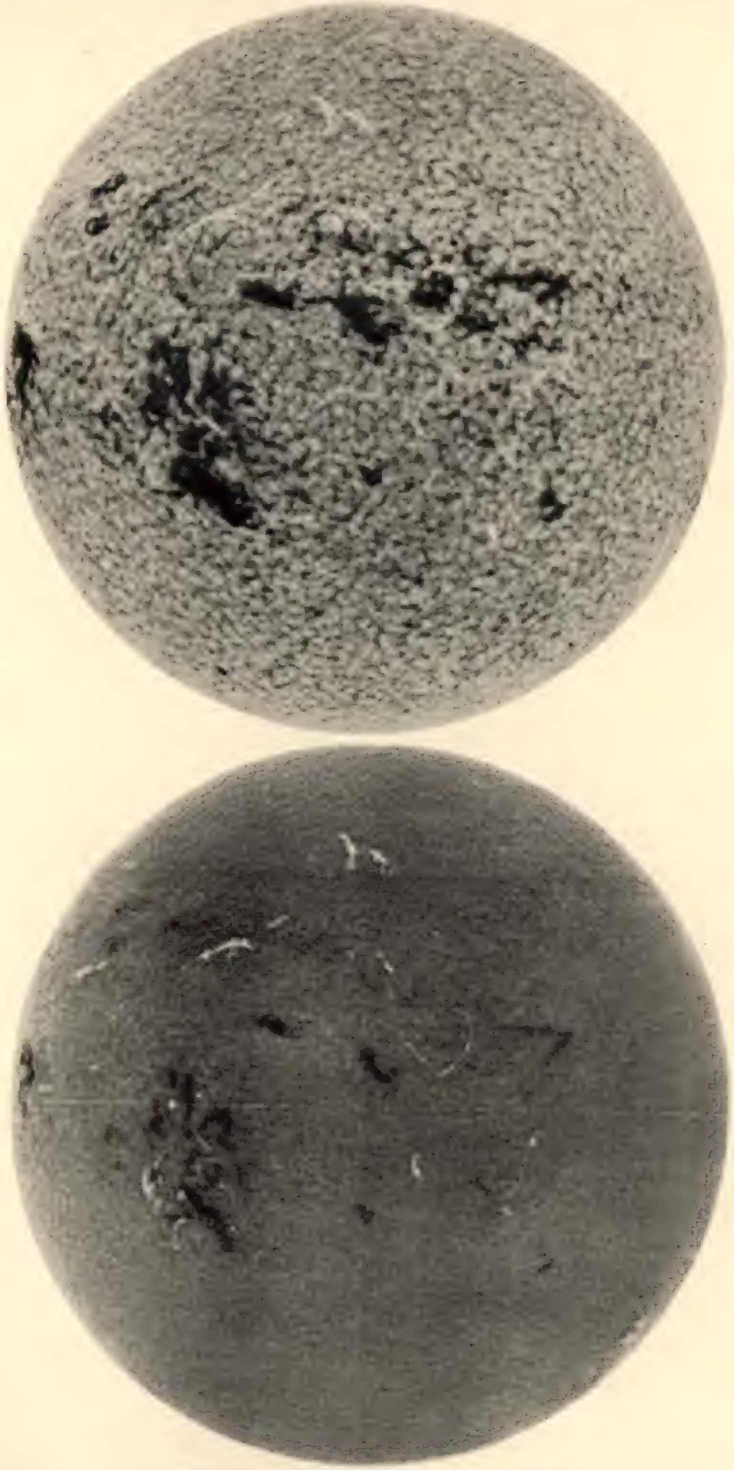
THE solar eclipse of 1836 played a very important rôle in the history of the development of the new science of astrophysics. The eclipse was visible at Edinburgh. It was not a total eclipse, however, but merely an annular one. At such an eclipse the angular diameter of the moon is smaller than that of the sun, with the result that at the middle of the eclipse there is a ring or annulus of sunlight visible around the edge of the dark moon. This eclipse was observed by Forbes. Referring to Brewster's discovery of atmospheric lines in the solar spectrum, Forbes clearly pointed out that the "telluric" lines were comparatively few in number and relatively unimportant compared with the very great number of solar lines. Moreover, he emphasized the fact that the Fraunhofer lines could not have been caused by the absorbing effect in our terrestrial atmosphere, for if this were true the spectra of the stars should be identical with that of the sun. As the spectra of the stars differed among themselves and were not always identical with the spectrum of the sun, it was manifest that it was not possible to imagine a terrestrial origin for all of the solar lines. Consequently, if the absorbing action of the earth's atmosphere could not be invoked to give an adequate explanation, there remained no other cause than that the origin of the lines must take place within the sun's own atmosphere. If, therefore, this was the true explanation, then an annular eclipse of the sun should furnish a crucial test. The terrestrial lines of the solar spectrum become more and more intensified as the sun's light reaches us through greater and greater layers of our earth's atmosphere, and in like fashion it appeared evident to Forbes that a similar effect must be visible in the lines of truly solar origin. And since the light

from the limb of the sun must pass through a much greater thickness of solar atmosphere than that from the sun's center, the lines from the sun's edge, observable at the time of the annular eclipse, should be much intensified in comparison with the Fraunhofer lines ordinarily visible from the sun's center. When the eclipse took place no change whatever was observed by Forbes in the number, position or intensity of the lines, and the obvious conclusion was drawn by him that, "This result proves conclusively that the sun's atmosphere has nothing to do with the production of this singular phenomenon."

To us living in the twentieth century, it seems passing strange that Forbes did not try the experiment of comparing the limb and the center of the sun by forming an image of the sun on the slit of his spectroscope by means of a projecting lens. This plan was undoubtedly in his mind as the following shows: "Had the weather proved unfavorable for viewing the eclipse, I intended to have tried the experiment by forming an image of the sun by using a lens of long focus, stopping alternately by means of a screen the interior and central moiety of his rays, and restoring the remainder to parallelism by means of a second lens, then suffering these to fall on the slit as before. The result of my experiment during the eclipse seemed, however, so decisive as to no marked change being produced at the sun's edges that I have thought it unnecessary to repeat it."

The scientific world in the first half of the nineteenth century knew little of laboratory methods and it was not at that time a habit of mind to test any theoretical conclusions by means of experimentation. In fact it was not until the year 1866 that the idea of Forbes was carried into execution and a projecting lens utilized for the examination of local phenomena such as the spectra of the limb or of sun spots.

In 1845, there was performed in England by W. H. Miller, the very experiment that later in Kirchhoff's hands was the crucial proof of the cause of the Fraunhofer lines. This experiment consisted in passing sunlight through various vapors heated to incandescence in a flame and noting the



Outer Layers of the Chromosphere

Photographed by Deslandres by Spectroheliograph at Mendon, France, on June 7, 1919. *Above:* K3 of Calcium; *below:* Hα of hydrogen. Note the differences in appearance of the two photographs and the fine detail that appears in the hydrogen photograph.

changes in the solar spectrum. He observed that in passing sunlight through glowing sodium vapor, the D lines were intensified. It is surprising that he appears to have sought no explanation of this amazing fact, and the surprise is all the greater since Miller's experiments were carried out with the express purpose of testing the theory that the Fraunhofer lines were actually produced by absorption in the sun's atmosphere.

This line of investigation was continued in 1849 by Foucault in Paris who was able to use a new method of heating salts and metals to the glowing point by the use of the electric arc. He focused an image of the sun on the arc itself and this procedure allowed him to observe at the same time the spectra of the arc and of sunlight. Incidentally he was surprised to discover the extreme transparency of the arc which caused only a faint shadow in the sunlight. This experiment manifested to Foucault that when the two spectra were exactly superimposed, the D line of sunlight was made considerably darker, proving that the arc absorbed the D rays; but that when, on the contrary, the two spectra jutted out one beyond the other, the D line appeared darker than usual in sunlight, yet stood out bright in the electric spectrum, thus demonstrating the perfect coincidence in position of the dark and bright rays. "Thus the arc presents us with a medium which emits the rays D on its own account, and which at the same time absorbs them when they come from another quarter." It was difficult to explain how it was possible for a glowing flame to furnish at the same time both bright and dark lines, — and the riddle of the solar lines seemed a hard one to solve. As early as 1850, Stokes seemed to have clearly grasped the solution of the problem, and he inserted a discussion of these matters in his university lectures at Cambridge.[1] Moreover, he seems to have been the first to localize the cause of the yellow D lines since he observed that the bright line was absent from a candle flame when the wick was snuffed clean, and from an alcohol flame when the spirit was burned in a watch-glass. Although he so clearly saw that the D lines,

[1] See Lockyer, *Chemistry of the Sun*, p. 51.

whether bright or dark, were caused by sodium vapor, and therefore correctly concluded that the absorbing effect of the sodium was in the neighborhood of the sun, he made no further experiments to test his deductions; and the honor for the great discovery waited another nine years. Thus again was demonstrated — which has frequently happened in the history of science — that though many investigators have converged towards the same goal of discovery, yet the prize has awaited the fortunate one who should make the critical experiment, which in itself at times has been one of little difficulty. Thus in 1855 Angström, and in 1859 Balfour Stewart by their experiments came very close to the true solution of the problem.

In 1859, Kirchhoff showed[1] for the first time that in order that sodium should be in a condition to absorb from the light of other sources it must itself be at a cooler temperature. " Fraunhofer has remarked that in the spectrum of a candle flame two bright lines appear which coincide with the two dark lines D of the solar spectrum. These bright lines can be easily intensified in a flame into which some common salt is put. I formed a solar spectrum by projection and I allowed the solar rays thus formed to pass through a strong salt flame before falling on the slit. If the sunlight were sufficiently subdued, then in place of the two dark lines D two bright lines appeared; if the intensity increased beyond a certain amount then the two dark D lines showed in much greater intensity than without the presence of the salt flame. The spectrum of the Drummond light contains as a rule the two bright sodium lines if the illuminating spot of the calcium cylinder has not long since passed the glowing point; if the cylinder remains undisturbed then these lines become weaker and finally completely vanish. If they have disappeared or are faintly visible, an alcohol flame into which cooking salt has been placed and which is brought between the calcium cylinder and the slit, causes two dark lines of exceptional blackness and sharpness, which in that respect agree with the lines D of the solar spectrum, to show themselves in their place. In this manner the D lines of the solar

[1] For complete details see Kayser, *Handbuch der Spectroscopie*, Vol. 1, p. 81.

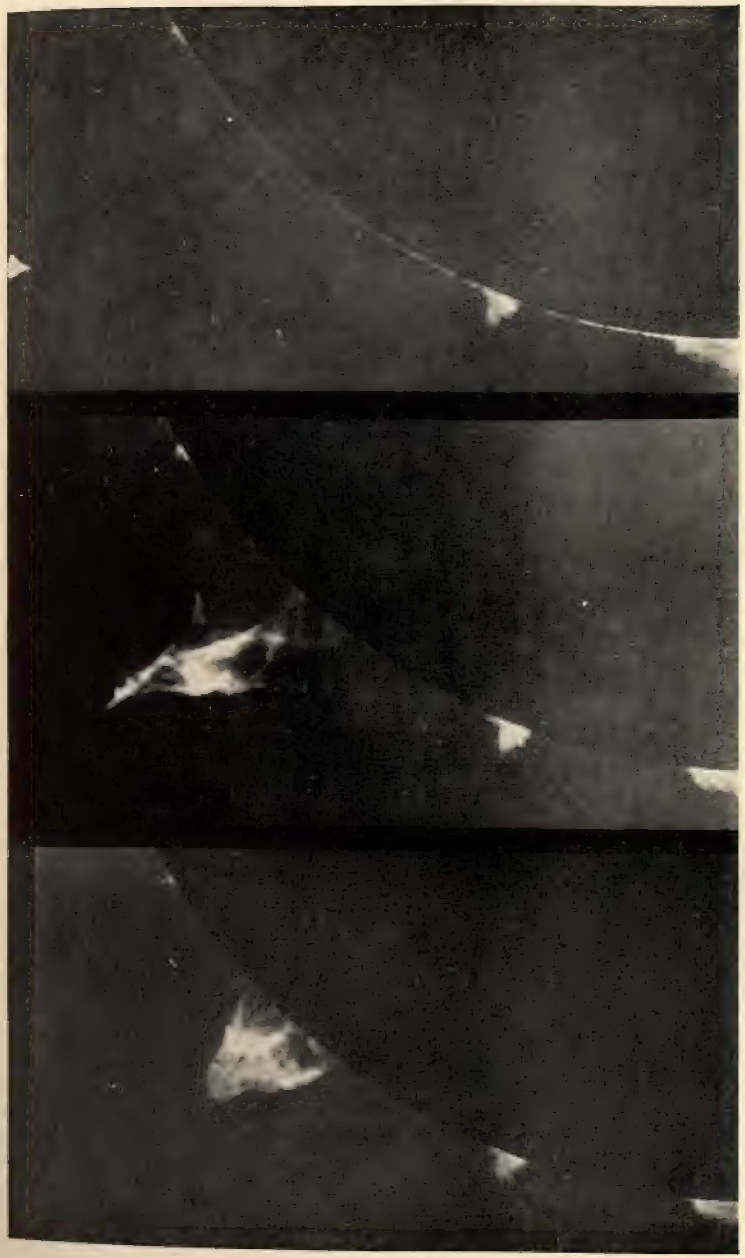
spectrum are artificially produced in a spectrum in which they are naturally not present. I conclude from these observations that colored flames, in the spectra of which bright sharp lines are found, so weaken rays of the color of these lines when such rays pass through the flames, that in place of the bright lines, dark ones appear just as soon as there is brought behind the flame a source of light of sufficient intensity in the spectrum of which these lines are otherwise lacking. I conclude further that the dark lines of the solar spectrum, which do not find their origin in the earth's atmosphere, are caused in the glowing solar atmosphere by the action of those substances which in the spectrum of a flame produced bright lines at the same place. We thus assume that the bright lines coinciding with D in the spectrum of a flame always arise from sodium contained in it; the dark D lines in the solar spectrum therefore allows us to conclude that sodium is found in the atmosphere of the sun. . . . In order that the D lines should come out dark in the spectrum of the Drummond light it is necessary to use a salt flame of lower temperature."

In these experiments, the salt flame was kept constant, the intensity of the sunlight being weakened or strengthened at leisure. In other words, this may be expressed by saying that the Fraunhofer lines in the spectrum of the sun are dark only in contrast with the more brilliant background of the sun itself. If this dazzling surface could be removed, and the comparatively dark lines of the solar spectrum could then be viewed against a background still darker, then by contrast the spectrum lines would appear as bright lines on a dark background where formerly they had existed as dark lines on a bright background. This change in the sun's spectrum, as we shall see later, takes place at the time of a total eclipse of the sun. The student of spectroscopy will save himself needless worry if he will remember that bright and dark are always to be considered as *relative* terms only.

A spectrum of bright lines on a dark background is said to be a bright-line, or an emission spectrum. On the other hand, a spectrum of dark lines on a bright background is called a dark-line, or an absorption spectrum. If a chemi-

cal element is heated to the point of vaporization, its spectrum consists of a bright-line spectrum. Sodium gives a very simple spectrum, consisting mainly of two very strong lines in the yellow part of the spectrum, the well-known D lines. If pure metallic sodium alone is used, the spectrum consists of these D lines. If the sodium is in chemical combination with chlorine, and the sodium chloride, or common salt, is heated to incandescence, the same D-lines due to sodium are shown in the bright-line spectrum. Or if any other compound of sodium is heated, the same D-lines result. The manner of the heating is of no consequence; a pinch of common cooking salt may be placed on the wick of an alcohol flame, a paper soaked in a saline solution may be placed about the burner of a Bunsen lamp, or a grain of salt may be put on the carbon of the electric arc or on one of the poles of an electric spark — the lines of sodium will always appear, the color of the lines will be exactly the same, and the wave-lengths of the lines will be unaltered no matter what the chemical compound in which the sodium is found or the manner of heating that salt to incandescence. Since the total light of the sodium consists mainly of two lines in the yellow, then when sodium is burning, it will give off yellow light only and the color of the flame will appear yellow to the eye.

If another element like lithium is examined, whether pure lithium or lithium in compound with some other element or elements, it will give its own peculiar spectrum of bright lines, and these bright lines will be found not to coincide with the D lines due to sodium. Since lithium burns with a red light, the prominent lines in its spectrum will be found at the red end of the spectrum. Some metals like sodium show a very simple spectrum, with very few lines; other metals show more lines, the greatest number of lines appearing for any one element being due to the presence of iron. It makes no difference how the iron is heated to incandescence, it makes no difference whether the iron is a piece of scrap or of polished steel, the spectrum will consist of thousands of bright lines in all the colors of the spectrum. Each of these many thousands of lines has its own particular



1 G.M.T. $4^h\ 15^m$ — 2 $4^h\ 58^m$ — 3 $5^h\ 45^m$

SPECTROHELIOGRAMS OF SOLAR PROMINENCES, MARCH 25, 1910

Photographed by Slocum with 40-inch Yerkes refractor. In (1) the height was 120,000 km. In (2) the maximum altitude was 240,000 km. The arrow in (3) shows a slight cloud at 290,000 km. altitude. Only one and one-half hours elapsed between (1) and (3).

wave-length. It is the business of the spectroscopist to find the value of the wave-length of each and every line. Some of the lines are faint, some strong, some are narrow, some broader, some are very sharp, others more fuzzy in appearance, but no matter what the quality of the iron or how vaporized, the spectrum is the same with lines of practically identical wave-lengths. Although there exist a great many chemical elements, the spectrum of each of which consists of many lines, while others of the elements have even thousands of lines in their spectra, it may almost be said that no line in any one spectrum coincides *precisely* with a line in any other spectrum. If, therefore, it is possible to determine the *exact* wave-length of a line in a spectrum, though the chemical origin of this line may be unknown, we shall have a ready means of identifying the elemental source of this line.

The principles upon which spectrum analysis depends are found in Young's *General Astronomy,* page 213, as follows:

1. A *continuous spectrum* is given by every incandescent body, the molecules of which so interfere with each other as to prevent their free, independent, luminous vibration; that is, by bodies which are either *solid* or *liquid,* or if gaseous, are *under high pressure.*

2. The spectrum of a gaseous element, *under low pressure,* is discontinuous, or in other words made up of *bright lines,* these lines being characteristic, that is, the same substance under similar conditions always gives the same set of lines, and generally does so even under widely different conditions.

3. A gaseous substance *absorbs* from white light passing through it *precisely those rays of which its own spectrum consists.* The spectrum of white light which has been transmitted through it then exhibits a " reversed " spectrum of the gas; that is, one which shows dark lines instead of the characteristic bright lines.

The third law, the great discovery of Kirchhoff, may be stated in other words as follows: The relation between the emissive power for each wave-length and the absorptive power for the same wave-length at the same temperature is identical for all bodies, and is in fact equal to the emissive

power of an absolutely black body at the same wave-length and temperature. We are quite familiar with a similar effect in the realm of sound. If a voice singing or speaking sounds a note of a certain pitch in a room where there is a piano, one string of the piano will vibrate in unison with the voice, the particular piano string taking its motion from the oscillations of the air. Similarly, a tuning fork in vibration will set in motion another tuning fork nearby which is tuned to the same pitch.

The work of Kirchhoff, therefore, in connecting the emission of light with absorption gives the means of determining the chemical composition of the sun. According to our present ideas, the photosphere of the sun, the portion of the sun we *see,* consists of gases under such very high pressure that the molecules cannot vibrate independently; and in consequence the spectrum of the photosphere must be *continuous,* a ribbon of light without breaks from red to violet. The photosphere is surrounded by a cooler layer of gases under low pressure, the so-called " reversing layer." If the spectrum of these gases could be examined entirely separated from the bright photospheric background, they would exhibit the gaseous, or bright-line spectrum. Under ordinary conditions, the light from the photosphere shines through the cooler gases of the reversing layer, and certain wave-lengths are there absorbed by the gases of the reversing layer, so that the spectrum of the sun comes to us as a reversed spectrum, of dark lines on a bright background; these dark lines, however, as stated above, are dark only in contrast with the much brighter photospheric background. To determine the constitution of the sun, it becomes therefore necessary to compare the bright line spectra of the various elements with the dark line spectrum of the sun. This comparison may be made by two different methods, either by viewing or photographing with a suitable instrument the spectrum of the sun and the comparison spectrum side by side, or by an exact determination of wave-lengths in the solar and in the comparison spectrum.

But the spectrum of the sun consists of many thousands of lines. It is evidently quite possible, and even highly

probable, that there should be very close agreement between some of the many lines in the sun and an equal number of lines in the spectrum of the element under investigation. These concurrences might be the result of pure accident. Kirchhoff investigated this possibility. A particular line in a comparison spectrum may exactly match in position a line in the solar spectrum. If the agreement is due entirely to chance, then by the laws of probability, it is equally probable that the line in the spectrum under consideration may or may not match a line in the sun's spectrum, or speaking mathematically the chance of an exact match taking place fortuitously is one out of two. If two lines agree in each spectrum, then the possibility of this happening by chance is but one out of four. Kirchhoff found sixty lines of iron to agree with sixty lines in the sun. The chance that this coincidence of all sixty lines is purely accidental is expressed by the number $\frac{1}{2}$ raised to the sixtieth power. At the present time over two thousand lines due to iron have been identified in the solar spectrum. If the coincidence of this large number of lines were the result of pure accident it would represent a chance of one in 2 raised to the 2000th power. This number is about equivalent to 100 followed by no less than 600 ciphers! (If one has nothing better to do, one might take a large piece of paper and put down the number one and follow it by six hundred and two zeros. Then one could divide it off into millions, billions, trillions, etc., and invent a name for this huge number!) The chance that the lines of iron and the Fraunhofer lines in the sun should agree in position entirely by accident is therefore infinitesimally small. But when in addition, we compare the appearance of the lines in the two spectra, and find that a strong line in the spectrum of the sun is matched by a strong line in the spectrum of iron, and a weak Fraunhofer line is matched by a weak iron line, then we see the utter impossibility of the coincidences being the result of mere chance.

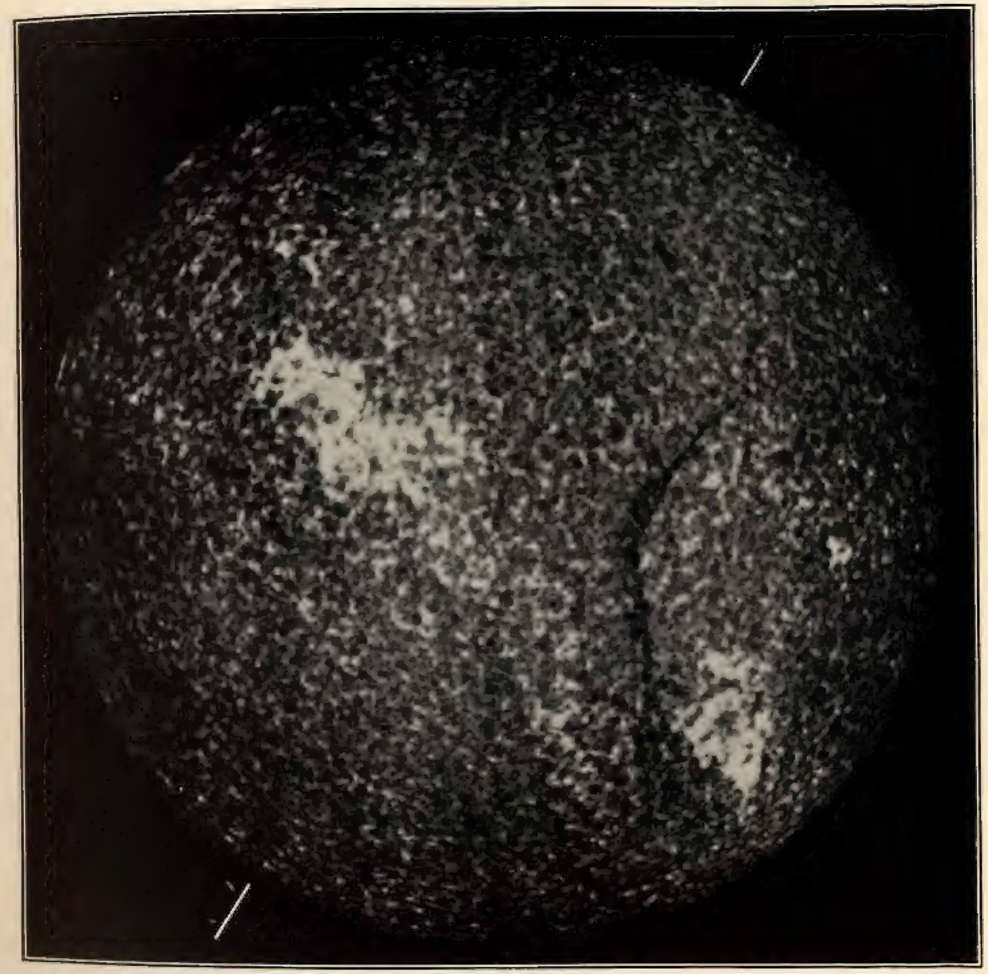
What is true of iron is equally true of the other elements investigated. It accordingly seems perfectly certain that we are able to ascertain the chemical constitution of the sun by means of the spectroscope even though we are looking

at the sun across a space of ninety-three millions of miles.

Astrophysics thus being placed on a very firm foundation, the infant science was immediately recognized throughout the scientific world to be of the very greatest importance to physicists, chemists and astronomers. But in spite of the almost universal recognition, there were a few doubting Thomases. In Chambers's very excellent *Descriptive Astronomy,* edition of 1867, page 27, is found the following: "Spectrum analysis has taken a start within the last two or three years, chiefly owing to the assertions made that it enables us to ascertain something about the physical condition of the sun. The subject is too purely a physical one, and also in too infantine a state to require notices in these pages at present, though the time *may* come."

It is remarkable to read the early history of spectroscopy and learn of the great opposition of certain scientists to the acceptance of Kirchhoff's proof; and it was but natural that there should be many claims to priority. By 1867, however, Pritchard of Oxford summarized the general feeling of the scientific world in the following words: "It may safely be asserted of Foucault in 1849, of Stokes in 1850, of Angström in 1855, and of Balfour Stewart in 1859, that each of them was in possession of an enunciated truth, which, had they traced to their natural and inevitable consequences, must have led to that grand generalization which will immortalize the name of Kirchhoff, and which forms one of the happiest and most remarkable discoveries of modern times."

With the trail so surely blazed, the path pointed out the direction of the researches to be taken by Kirchhoff's successors. The quest had a two-fold interest, for not only did the new method serve as an infallible chemical test of terrestrial substances, but it gave also a ready means of determining the constitution of the sun and also of the more distant suns, the stars. Physicists, astronomers and chemists vied with each other in pushing forward the researches as rapidly and thoroughly as possible, and opticians and instrument makers came to the assistance of the scientists



Spectroheliogram showing dark Calcium Flocculus
Photographed by Evershed March 23, 1910 at Kodaikanal Observatory.

by furnishing improved forms of apparatus. It was manifestly necessary to investigate the solar spectrum and the spectra of the various chemical elements. These investigations had necessarily to be carried out with the spectra, produced on as large a scale as possible, and the measurements of the positions of the lines required the very highest degree of precision attainable. To denote the position of a line, some more accurate method was necessary than that of placing it in the red or blue of the spectrum. Fraunhofer and also Kirchhoff used a rather arbitrary scale. Newton proved that a difference in color meant a difference in refrangibility. Fraunhofer went a step further and demonstrated that a difference in color meant a difference in the length of the wave causing the light. Since the time of Thomas Young, 1802, it has been known that light is a wave phenomenon, the waves, somewhat similar to water waves, moving transversely to the direction of motion. The length of the wave from crest to crest, or from trough to trough, is known as the wave-length, and this length might be measured in fractions of an inch, or foot, or meter. All scientists, whether they live in America or in Germany, or whether they speak English, Japanese or Russian, now use the meter as the unit for measuring the wave-length of light. A meter divided into ten thousand million parts, or 10^{10} parts, is called a "tenth-meter." This very small distance is known as the "Angström Unit," or more simply as the "Angström," and it is the unit for measuring wave-lengths. The position of a line is known by its wave-length, and the more precise the investigation the more accurately de we need to know this quantity. The K-line in the solar spectrum has a wave-length according to Rowland of 3933.-826. This is printed either as λ 3933.826, or 3933.826 A. (We shall adopt the latter notation.)

Knowing the wave-length of light of a certain color, it is a very simple matter to calculate the number of waves that enter into the eye in a single second of time. All that is required is to know the velocity at which light travels. It is now known that light of all colors, whether red, blue or violet, travels at the same rate of speed, viz., the almost

incredible velocity of 186,330 miles, or in round numbers 300,000 kilometers per second. To simplify the calculation, suppose the light is violet, of wave-length 4000 A. The length of these waves from crest to crest is 4000×10^{-10}, which is 4.10^{-7} meters (i.e. 4 divided by ten million). 300,000 kilometers per second is 300,000,000 meters or 3.10^{8} meters per second. If therefore we divide the distance that light travels in one second by the wave-length, we will find the number of waves. For light of 4000 A, seven hundred and fifty millions of millions (750,000,000,000,000) of waves enter into the eye in one second of time. If the light under consideration is red instead of violet, inasmuch as the wave-length of the red is longer than that of the violet, fewer red waves will consequently enter into the eye in a given time. These tiny waves impinge on the retina of the eye, creating motions which when telegraphed to the brain cause the sensation of violet or red light. The mechanism by means of which the minute motions produced in the eye by light waves cause the sensation of light has never been completely discovered. Professor John Joly in *Philosophical Magazine, 42,* 289, 1921, gives a very plausible explanation based on the quantum theory. He assumes that the origin of vision and color perception is to be sought in the liberation of electrons under light stimulus within a photoelectric substance or substances existing in the retina. In the case of the rods, rhodopsin, being such a photosensitive substance, acts as the basis of vision, and it is assumed that the same substance in the cones is responsible for the color vision. The sensitivity of the eye to faint light is extraordinary. Henri and des Baucels have found that the retina is sensitive to a minute amount of light energy which, when expressed in physical units, amounts to 5×10^{-12} erg. The quantum for green light is 4×10^{-12} erg, and hence it is assumed that one quantum, by the liberation of a single electron, is sufficient to cause the sensation of light. The action taking place in the eye seems to be quite analogous to that occurring in the light-sensitive film of the photographic plate, the latent image being caused by the movement of electrons.

The new method of research in the hands of Kirchhoff soon resulted (1861) in the discovery of two new chemical elements, caesium and rubidium. The spectroscope manufactured by Steinheil consisted of four prisms, three of 45° and one of 60°. The collimator and telescope had apertures of one and a half inches, with a focal length of eighteen inches. One half of the slit was covered by a totally reflecting prism by the aid of which two spectra could be examined side by side and direct comparisons made. Unfortunately, it was necessary to set to minimum deviation by hand, a very slow process, and as a consequence Kirchhoff shifted the prisms only occasionally, a procedure which greatly impaired his measures. He investigated the spectra of a large number of elements, and also measured the positions of the lines in the solar spectrum from A to G, though at first he only published the region from D to F, since his eyes could not stand the strain of such continuous measurement and failed him. His measures being referred to an arbitrary scale, it was necessary to reduce them to wave-lengths, and this was done later by Airy, Gibbs, Watts and Hasselberg.

It has been said with great verity that these were splendid days for the laboratory scientist for the reason that each and every observation, no matter how trivial, was almost certain to prove to be a new discovery. Without attempting to trace the details in the further development of the new science, we shall try to give only the more important names in the honor roll of fame: Plücker, Hittorf, Crookes, Miller, Huggins, Rutherfurd, Angström, Secchi, Janssen, Lockyer, Young, Vogel, Cornu, Liveing and Dewar. In the twenty years following Kirchhoff, no less than ten new elements were found by the aid of the spectroscope. Naturally many mistakes were made and wrong conclusions drawn. The chief cause of the mistakes was the presence of many impurities in the elements investigated and hasty identification of lines through insufficient accuracy in wave-length determinations.

A new epoch in the history of spectrum analysis was inaugurated in 1882 by the work of Henry A. Rowland, whose

gratings,[1] plane and concave, permitted a hundred-fold increase in accuracy in the determination of wave-lengths. Rowland's success came through the construction of a long screw, almost free from errors, mounted in a dividing engine in such a manner that it was practically possible to eliminate the few remaining errors of the screw. The precision that must be attained in the manufacture of gratings of the very first quality may be stated as one requiring that the average line of the grating shall be correctly placed to about one one-thousandth part of the grating space. This, for the finest Rowland gratings of 20,000 lines per inch, means that each line ruled on the grating must not on the average differ from its true position by so much as the minute quantity of one twenty-millionth part of an inch!

The highest degree of success was attained by ruling with a diamond point on speculum metal, the incident light thus being reflected from the grating surface. Gratings were ruled both on plane and on spherically concave surfaces. The largest Rowland gratings were six inches in diameter, and ordinarily the greatest radius of curvature for the concave gratings was twenty-one and a half feet. The concave gratings reduced the spectroscope to the greatest simplicity of slit, grating and photographic plate. No lenses of any kind were necessary to bring the light to a focus, and hence all aberrations introduced by the lenses and all absorption of light by the glass were eliminated, with a consequent great increase in the extent of the ultra-violet region. The concave grating is generally used in the laboratory with the "Rowland mounting" possessing two tracks for carrying grating and photographic plate perpendicular to each other, the slit being placed accurately at the intersection of the two tracks. If grating and photographic plate are each perpendicular to the arm joining the two, there then results a "normal" spectrum, or one in which the distances between the lines are directly proportional to the wave-length.

Compared with prisms, concave gratings have the following advantages: (1), An enormous increase in dispersion, definition and resolving power. To equal Rowland's gratings in these respects, in the neighborhood of the D lines, it would be necessary to have prisms of the very first quality added to prisms with a total prism base of fifty inches of glass. (2), The spectrum produced by the grating is "normal" and not "prismatic," thus permitting wave-lengths to be determined with much greater facility and much greater accuracy. (3), A much greater extent of the ultra-violet is secured. (4), The astigmatism of the grating increases the length of the lines, and this principle, combined with the overlapping of images from the spectra of different orders, not only permits a great increase in accuracy, but also a more ready determination of absolute wave-lengths. The grating, however, has some disadvantages, chief among which is that the incident light is divided between the central beam and many different orders of spectra, with the consequent result that there is a great weakening of light in any one spectrum. In the investigation of objects giving little light, like the stars, prisms are almost universally used. In most laboratory researches and in work on the sun, gratings are generally used. Although Rowland's method of grinding the screw was not a secret, it is only in comparatively recent times that the excellence of the Rowland gratings has been equalled by others, by Michelson of the University of Chicago and by Anderson of the Mount Wilson Observatory.

[1] See Kayser, *Handbuch der Spectroscopie*, Vol. 1, 121 and 397. See also article Screw, *Encyclopaedia Britannica*.

Coincident with Rowland's manufacture of the grating came the discovery of the modern photographic dry plate with its great increase in sensitiveness. The two most important pieces of work in this new epoch of discovery in astrophysics have been Rowland's great map of the solar spectrum, and the publication in the *Astrophysical Journal* of the wave-lengths of the lines in the solar spectrum with the tracing of as many lines as possible to their chemical origins. The more prominent names connected with investigations in the laboratory and on the sun itself are: Rowland, Jewell, Kayser, Runge, Paschen, Rydberg, Eder and Valenta, Exner and Haschek, Langley, Abbot, Schumann, Lyman, Humphreys, Zeeman Hale, Deslandres, St. John, Saunders and Fowler.

CHAPTER VII

THE SURFACE OF THE SUN

AT THE time of the Greeks how simple it was to explain all of the known facts about the sun! No supposition was necessary other than that the sun was a ball of fire. It was not at all known what fire was beyond the fact that heat was manifested,— but this deficiency in knowledge seemed of little importance. As a further illustration of the elemental beliefs of primitive peoples there might be given the following legend regarding the origin and motion of the sun which is found among the Yuki tribe of American Indians.[1]

" In the beginning there was no land; all was water. Darkness prevailed everywhere. Over this chaos of dark water hovered On-coye-to who appeared in the form of a beautiful white feather, hence the love of the Yukis for feathers. In time the spirit became weary of his incessant flight through the murky space and lighted down upon the face of the water. Where he came in contact there was a whirlpool that spun his body round and round. So rapid became the motion that a heavy foam gathered about him. This became more dense and expanded in width and length. It gathered up the passing bubbles until it was a huge floating island. On the bosom of this rested the snowy form of On-coye-to. As he lay upon this island for an almost endless flight through the dark space, the idea of a permanent resting place came into his mind. So he made the land and divided it from the water. From the form of a feather he assumed that of a man, and rested upon the land. Still there was no light, and his spirit was troubled. On-coye-to saw afar off in the firmament a star, 'po-ko-lil-ey,' and resolved to visit it and learn how it emitted its sparkling

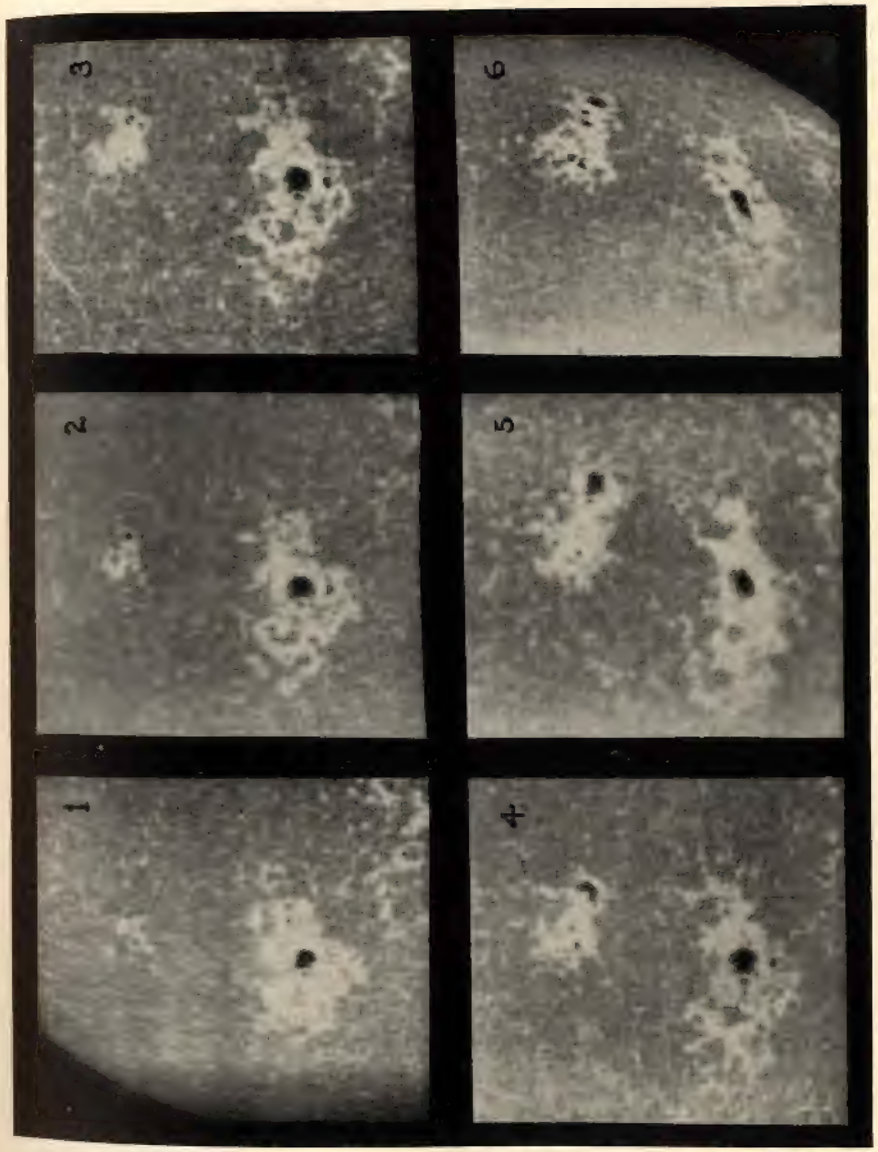
[1] *Smithsonian National Mus. Report,* 326, 1902.

light. After a long journey, he arrived there and found a large and beautifully lighted world, inhabited by a numerous, hospitable people. Still, he saw not whence came the light. He was allowed free access to all habitations save one, the 'sweat house.' This was guarded night and day, and was accessible only to sick persons. Finally a great hunt was planned, and as time drew near all was prepared for the occasion. But On-coye-to feigned sickness that he might investigate the sweat house. When the morning arrived for the hunt he was too ill to acompany the hunters. A council was held to determine whether this stranger should be admitted to the sweat house, which is even now a sacred place with the Yuki tribe, and it was decided to give him the benefit of this house of medicine. A few old men were left to administer to his wants and to see that all went well. As he entered the sweat house he was almost blinded by the light that flashed upon him, but as he became accustomed to it, he looked around him and discovered its origin. Hanging high over his head in several baskets were as many beautiful suns. Having found the fountain of light he waited patiently until the old men were all asleep, then climbing cautiously to what seemed the brightest of the suns, he seized it, slipped from the sweat house and made his way rapidly towards his own world. He was hotly pursued by the indignant warriors, but he arrived safely after many adventures. He hung the sun in its basket in the far east, then surveyed it. It did not light up to suit him, and he moved it a little higher. Still it did not suit him, so he continued to move it, on and on. And he is moving it to the present day." Thus the Indian accounts for the moving of the sun, and thinks not that the earth moves.

As knowledge has gradually been accumulated regarding our central luminary, and as information is secured about the laws, physical and chemical, to which the sun is subjected, the more and more difficult has become the problem of finding an explanation adequate to satisfy all of the facts. And now in the twentieth century, it is discovered that each and every one of the countless billions of chemical atoms

that form the sun is a solar system in miniature, with the result that solar theories must be revised and hypotheses revamped in order to take account of electrons and protons. The sun is a typical star, but owing to its proximity it may be examined in detail, its surface, the spots that are of such great interest, the reversing layer, the chromosphere and the far-flung corona. The stars are so far distant that they appear practically as points of light even in our largest and best telescopes, and consequently little more can be learned of them than what depends on their surface brightness. On account of the closeness of the sun, its surface may be covered up by the interposing moon, and as a result, envelopes of chromosphere and corona are shown. Although similar envelopes unquestionably exist on the stars, they can never be made manifest to us. By the study of eclipses a wealth of knowledge is acquired concerning the sun, but to gain an adequate idea of what additional information is thus secured, it will be well to give a brief résumé of the salient points of solar research.

Compared with terrestrial standards, the distance to the sun is colossal and its diameter enormous. The problem of finding the distance of the sun is one of the most important as well as one of the most difficult in the whole of the science of astronomy. The importance lies in the fact that the distance from earth to sun is the unit for measuring all celestial distances, except that to the moon, the solar distance being called the *astronomical unit*. The yard, or the meter, is the standard of length for all measurements in civilized countries. The "standard yard," or the "standard meter," is a bar of certain composition, of definite shape, whose length can be determined by precise measurements at known temperatures. The standards are kept in London or Paris, but various prototypes are widely distributed. Certain advantages would result from the employment of but one standard of length, the meter, which is now almost exclusively used in all scientific measurements. The reason is not because the length of the meter is more valuable than that of the yard, but rather that the decimal system employed with the meter is simpler than the



SPECTROHELIOGRAMS SHOWING DEVELOPMENT OF COMPANION SPOT
Photographed May 1907 by Fox and Abetti with Yerkes refractor.
Scale: Sun's Diameter = 6 inches.

more cumbrous division of the yard. At the end of the eighteenth century the meter was designed by the French to represent the ten-millionth part of the quadrant of the earth, so that its circumference should be exactly forty million meters. At that time, however, the size of the earth was known with little accuracy. If, therefore, the meter were actually to represent a certain definite and fixed fraction of the earth's size, it would be impossible to use it as a standard for the reason that its length would change with every revision of the earth's measurement as new geodetic operations were carried out, and would alter with any variations in the earth itself, which changes geodesy and geology tell us are continually taking place.

By means of the careful researches of mathematical astronomy stretching back over hundreds, and even thousands of years, an accurate plot can be drawn to scale of the orbits of all the planets and satellites of the solar system. The periods of each have been determined accurately, the shapes of their orbits, their inclinations to the ecliptic, etc. All of the planetary distances have been found by the astronomer by referring them to the astronomical unit, the distance from earth to sun. To know the complete scale of the astronomical plan in miles, it is necessary to know accurately at least one distance, either that of the earth to the sun, or to one of the planets. Manifestly, the nearer the planet, the more accurately can the distance from the earth be determined. Celestial distances are usually found by the methods of the surveyor who wishes to ascrtain the width of a river which he cannot traverse. A base-line is measured with as great precision as possible, and from each end of this base-line, angles are measured to some well-defined object on the other side of the river. A civil engineer would be in a quandary if a base-line of only three inches in length was available for measurement on his side of the river and it was necessary to determine, with the precision necessary for planning a cantilever bridge, the distance across the river. This is exactly the problem that confronts the astronomer in attempting to measure directly the distance of the sun, since the only base-line available is a

chord of the earth. Instead of expressing the distance to the sun in miles or kilometers, the astronomer knows this unit ordinarily by means of the small angle at the sun subtended by the earth's radius, and this angle is called the "solar parallax." As there are many different solar radii, the earth not being a sphere, the equatorial radius is assumed. The astronomical unit when expressed in miles must therefore be subject, not only to all of the errors of the astronomer in carrying out his measurements, but also to those due to the work of the geodesist in determining the shape and size of the earth and in referring these measures to the standard yard or meter.

Although this is not the place to discuss the details of the determination of the solar parallax, brief references will be made to the more promising methods. It is impossible to secure the distance to the sun by direct measures and recourse must be had to the determination of this distance indirectly by the measurement of other distances in the solar system. Great were the expectations aroused by the transits of Venus in 1761 and 1769, and again in 1874 and 1882. By the year 1882, the dry plate had been invented and it was anticipated that photography would revolutionize our knowledge of the fundamental unit. But alas! the "black drop," and the atmosphere of Venus caused the observations to be practically a dismal failure. Another attempt by this method will not be possible until the year 2004, the year of the next transit of Venus.

Great advances in precision were made by Gill in his measures of Mars and some of the minor planets by means of the heliometer. The discovery in 1898 of the planetoid Eros, which at perihelion comes closer to the earth even than Mars, gave to the astronomer a splendid opportunity of determining the solar parallax for the reason that photography could be applied to the problem. Although much was acomplished at the opposition of 1900–01, when Eros at its nearest approach was 30,000,000 miles from the earth, more will be effected in 1931 when the planet comes to within half this distance.

Methods based on the law of gravitation furnish the

means of determining the distance of the sun. E. W. Brown's magnificent investigation of the motion of the moon gives 8.″778 as the value of the solar parallax. Other gravitational methods furnish the mean value of 8.″780.

The velocity of light can be utilized in three different manners: (a) by the constant of aberration; (b) by the eclipse of Jupiter's satellites; and (c) by the velocity of the earth in its orbit by utilizing the Doppler principle of measuring the motion in the line of sight from spectra of stars or of planets. St. John and Nicholson at Mount Wilson, using large dispersion on the spectrum of Venus, find the solar parallax of 8.″813. (*Publications A. S. P.*, *32*, 332, 1920.) They give also the values by other observers.

A summary of the best values[1] of the solar parallax (see Abbot, *The Sun*) are:

From heliometer work on minor planets	8.″807
From the Eros campaign	8. 807
From all gravitational methods	8. 780
From the eclipses of Jupiter's satellites	8. 799
From the velocity of light and constant of aberration (20″.47)	8. 803

The present accepted value of the solar parallax is 8.″80, corresponding to a distance of the sun of 92,900,000 miles, with an uncertainty of about 50,000 miles, or an error of about one part in 2000. To walk the distance to the sun at four miles per hour and ten hours per day, 68 years would be necessary for the first million miles, or 6300 years for the total distance. An express train going at sixty miles per hour would take 175 years, while light which travels at the great speed of 186,330 miles per second takes 499 seconds.

If we know the angular diameter of the sun we can readily find its linear diameter of 865,000 miles, which is 109.5 times the diameter of the earth. Perhaps the best method of visualizing the huge size of the sun is to compare it with the distance to the moon, which in round numbers is 239,000 miles. If the earth could be placed at the center of the sun and the moon were allowed to revolve in her orbit about the

1 See also, Newcomb-Engelmann, *Populäre Astronomie*.

earth there would be plenty of room inside the sun for the moon to make her monthly journey, since the moon would be little more than half way out to the sun's surface. A spot on the sun having a diameter of 8000 miles, or the size of the earth, would be regarded as fairly small and a telescope would be needed to detect it. Dividing the linear diameter of 865,000 miles by the angular diameter 1920″, it is found that 1″ at the sun corresponds to 450 miles, which is equivalent to 725 kilometers. These are useful quantities to remember, especially when considering the subject of eclipses.

Since the surfaces of spheres are proportional to the squares, and the volumes proportional to the cubes of their radii, it is readily found, by squaring and cubing 109.5, that the surface of the sun is 12,000 times that of the earth while its volume is 1,300,000 times the volume of the earth.

The mass of the sun is 332,000 times the mass of the earth, a relation that can be determined by comparing the distance a body falls towards the earth in a second of time in obedience to the law of gravitation with the distance that the earth falls towards the sun in the same interval of time and also in obedience to the law of gravitation. In one second the earth travels eighteen and a half miles of her annual journey about the sun, but as this is accomplished without friction we feel no sensation from this rapid flight. In going eighteen and a half miles, the earth deviates but one-ninth of an inch from a straight line. As the earth weighs six thousands of millions of millions of millions of tons, which is 6×10^{21} tons, the sun weighs 2×10^{27} tons. This is such a colossal number that it makes little difference in our comprehension of it whether it is the American ton of 2000 pounds, or the English ton of 2240 pounds, or the long ton that we pay for when we buy coal or the short ton that is furnished by the dealer when the coal is placed in the bin.

Knowing the mass and volume of the sun compared with that of the earth, we find the density of the sun is 0.255 times that of the earth, or about 1.4 times the density of water. The attraction of gravity at the surface of the sun is 27.6

times that which it is at the earth's surface, so that a man weighing 150 pounds would weigh over two tons if transported to the sun, and his feet would be so heavy, even if the footing were secure, that he would not have strength sufficient to lift them.

The small density of the sun, being only one-quarter that of the earth, is one of the most significant bits of knowledge connected with the study of the sun. All theories of evolution point to the fact that the sun and earth are made of the same materials. Indeed Rowland was wont to say that if the earth were heated to incandescence it would give a spectrum identical with that of the sun. The low density makes it evident that the sun cannot be a solid like the earth, nor indeed can it be a liquid, and it must therefore be a gas, the terrific heat of the sun being sufficient to vaporize all known terrestrial substances. The condition of immense heat and enormous pressure caused by gravitation on the sun cannot be even distantly approximated in our laboratory experiments. Unquestionably the sun does not obey the laboratory laws to which such perfect gases as oxygen, nitrogen and hydrogen are subjected. For the complete explanation of solar phenomena it is necessary to proceed from known conditions to those impossible to duplicate in the laboratory by the difficult and uncertain methods of extrapolation. The steps of scientific development must accordingly be carefully planned and wisely thought out, or else the path of truth may lead away from the goal of progress rather than towards it.

The spherical portion of the sun that we see is called the *photosphere*. According to Young, *The Sun*, page 109, the "photosphere is a sheet of self-luminous cloud; possibly like the clouds of our own atmosphere, with the exception that the droplets of water which constitute terrestrial clouds are replaced in the sun by drops of molten metal, and that the solar atmosphere in which they float is the flame of a burning fiery furnace, raging with a fury and an intensity beyond all human conception." This notion of the photosphere propounded a third of a century ago has been somewhat modified by modern research. By means of convection cur-

rents, gases from the interior of the sun are brought to the surface. There set free from the enormous internal pressure and meeting the cooler temperatures of outside space the gases expand. The pent-up energy being suddenly released, there is a rapid fall of temperature, and according to Young's theory, small solid or liquid particles are formed. By gravity these sink back to the solar furnace, there to be changed again to the gaseous form. The rising and falling back again to the solar surface of the "drops of molten metal" cause a continued rain of meteors on the sun's surface. These "drops" play a very important rôle in many solar theories, but particularly in that of Arrhenius regarding radiation pressure (Chapter XIX). The temperature of the photosphere "seems to be certainly in excess of 6000° absolute, Centigrade. There are no substances, so far as known, which can exist except as vapors in these conditions. Hence, it seems reasonable to suppose that the sun contains no solids or liquids, unless perhaps in sun-spots, and that its substance, as we see it, and within the layers we see, is altogether gaseous."[1]

In carrying out investigations regarding the sun's surface there are two points of view that astronomers should never forget. The first is that the photosphere can be viewed or photographed only *through* the superposed layers of the solar atmosphere. The photospheric spectrum which must be continuous from red to violet without breaks, can never be obtained. The second point to be remembered may be visualized by analogy with the earth. At an elevation of three and a half miles above sea-level, atmospheric air has its density cut in half. But gravity at the sun is nearly twenty-eight times its value on the surface of the earth. Allowance being made for the hundred-fold diameter of the sun when compared with that of the earth, it is seen that within ten or twelve miles of the sun's surface there would exist one-half of the total material in the sun's various layers of gases were it not for the enormous temperature of the sun. The decrease in pressure upwards from the sun's surface is consequently extremely rapid. The importance of

[1] Abbot, *The Sun*, p. 243.

this point cannot be over-emphasized, since most investigators seem to forget that the change in pressure must take place at such a very accelerated rate.

The sun may be viewed with a telescope by the use of solar eye-pieces of various kinds; or by projecting the sun on a screen, the solar image being brought to a focus by slightly drawing out the telescopic ocular. If the telescope is of moderate size, and the definition good, the surface of the sun looks like "rough drawing paper, or like curdled milk seen from a little distance." The use of a large telescope and of moments of exquisite seeing that come but rarely reveal an infinite wealth of detail. The best drawings of the sun are by Langley who describes the surface of the sun as that of "snow-flakes sprinkled sparsely over a grayish cloth." Before the application of photography great was the diversity of opinion concerning the ultimate nature of the light-giving particles of the sun. We learned then of "rice grains," of "willow leaves," of "thatch-straw" and of "granules"; and the various camps in favor of one or other designation were about equally divided.

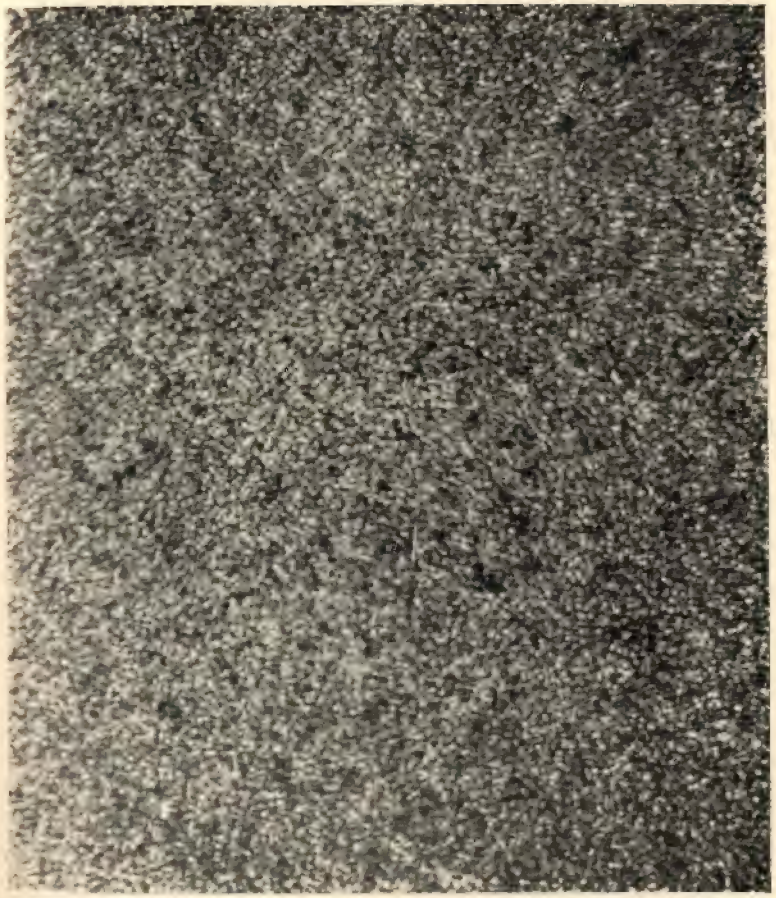
Photographs of the sun may be obtained by the method known to the great host of camera users, that of the focal-plane shutter. This consists essentially of a slit of variable size that can be driven by means of a spring across in front of and close to the photographic plate. By regulating the width of the slit opening and the tension of the spring, exposures may be varied at will. The exposures necessary to obtain good photographs of the sun depend mainly on the size of the telescope, the sensitivity of the photographic plate and the method of development. The modern dry plate of great rapidity does not permit the securing of solar photographs of the greatest detail. With the sun, where there is such an abundance of light, it is unnecessary to make use of the fastest plates which are primarily for the purpose of decreasing the exposures. Better results may be secured by the use of finer grained, slower and more contrasty plates. As a matter of fact, the modern dry plate cannot furnish the exquisite definition secured by the old wet-plate process, and for this reason the superb solar photo-

graphs of Janssen at Meudon are unsurpassed even at the present day.

The best conditions for observing the sun are found not more than one per cent of the time spent at the telescope. Under these maximum conditions, the skilled eye can see finer details than can be portrayed on the photographic plate. According to Langley, the " snow-flakes " are in the neighborhood of 50 to 100 miles in diameter, and these in turn are made of flakes similar in form, but of one-fifth the dimensions. These small particles cover but one-fifth of the surface but radiate three-quarters of the total solar light, and hence they must shine with an intensity twenty-fold that of the darker portions of the sun.

The most noticeable feature of photographs showing the whole solar disk is the darkening that is found near the edge of the sun. This darkening is caused by the absorption by the sun's atmosphere, a beam from the limb of the sun passing through a greater layer than one from the center. The sun or moon when rising or setting looks reddish to us on account of the absorption of the blue and violet by our terrestrial atmosphere. In a similar manner, the solar atmosphere absorbs more and more of the violet end of the spectrum as the limb of the sun is approached, and the maximum of radiation is displaced towards the red. A similar shifting of the wave-length maximum is found when comparing the spectrum of a sun-spot with that of the photosphere. Abbot (*The Sun*, page 107) gives measures of the distribution of radiation over the sun's disk from the center outwards to the edge. If the sun could be viewed without the absorptive effects of its own and the earth's atmospheres, the maximum intensity in the spectrum would be shifted by an appreciable amount to the violet, and the sun instead of appearing as yellow in color to the eye would look bluish.

The exquisite photographs of Janssen show the solar granulation in splendid detail, the features being sharp and well-defined. Other parts of the same photographs are quite smudgy in comparison, as if the solar surface were in violent commotion. To these parts Janssen gave the name *réseau photosphérique*. If photographs taken in rapid succession



THE SUN'S SURFACE

Photographed by Janssen at Meudon, September 9, 1883, *"Like snowflakes sprinkled over a grayish cloth."*

are examined it is found that the smudgy and ill-defined portions exist at different parts of the solar image. The simplest and most apparent explanation seemed to be that these changes afforded positive evidence of violent commotion on the sun which certainly must exist there on account of the very high temperature. This evident explanation, however, seems not to be the true one. Any motion of the atmosphere of the sun, or of the earth's atmosphere close to or far away from the photographic plate would have the effect of blurring the photographic image. To make a long story short — the general opinion regarding the *réseau photosphérique* is that it is not a solar phenomenon at all, but is caused by the disturbance of the air heated in the telescopic tube by the sun's beams. The portions of the photograph in good definition represent the true granulation of the solar surface. Direct photographs similar to those of Janssen have been made by Hansky of Poulkova and Chevalier of the Zô-Se Observatory in China. Exposures made in rapid succession give the following information regarding the ultimate nature of the photosphere as depicted by photographs: (1), The solar granules have a diameter of 400 to 1200 miles, though at times smaller granules are seen no more than 100 miles in diameter. (2), They are generally circular, or elliptical in shape. (3), They coalesce to form larger particles. (4), These granules are the "clouds" of Young's theory. (5), The life of one of these clouds is very short, the majority of them last for approximately half a minute, and practically none exist longer than a few minutes. (6), The displacements vary widely in direction and in velocity. The movements range from zero to thirty kilometers per second, though occasionally higher speeds are observed. (7), The granules in fact seem to be the summits of a fleecy structure of condensed particles. In fact, they represent [1] on an enormous scale a phenomenon similar in appearance to a storm-tossed and choppy sea when viewed aloft from an airplane.

The most prominent features of the solar surface are the spots. Individual records of these exist as far back as the

[1] Astrophysical Journal, *27*, 12, 1908.

Chinese, but their real history begins with the invention of the telescope; and they were independently discovered by Galileo, Fabricius and Scheiner. There is a great wealth of scientific literature connected with the study of spots — but here it will be possible to give only the salient features, and a brief summary of our present knowledge, which, alas! is far from complete. As in the study of the photosphere, the details of the appearance of spots can be better observed visually than by photography. A normal spot consists of an *umbra,* more or less round, surrounded by a less darkened *penumbra,* the structure of the constituent parts of a spot differing much from each other and from the surface of the photosphere. The roundish shapes of the granular photosphere are changed in appearance to the straw-thatch of the penumbral filaments which exhibit a great wealth of detail, and these in turn transform into the smooth, black, velvet-like appearance of the umbra. The umbra is, however, not uniformly black but is more or less cloudy in appearance when conditions of seeing are at the best. Generally associated with spots are the *faculae,* or bright patches on the sun. These exist at slight elevations above the average surface of the sun, and are best seen when near the edge of the sun where the greater absorption of the sun's atmosphere and the elevation of the faculae make them visible by contrast with the darker surroundings. The umbra of a spot is dark only by contrast with the more dazzling photosphere, yet withal it is not black, for it is more brilliant than the electric arc. During the progress of an eclipse of the sun a spot has been observed by Evershed to be much brighter than the dark limb of the moon occulting it. Langley estimates that the blackest spot gives 500 times as much light as an equal area of the full moon.

Spots vary in size, from a few hundred miles to 50,000 miles in diameter in the case of the very largest spots. Groups of spots may extend across one-sixth of the diameter of the sun, and consequently may be visible to the naked eye when the sun is seen through haze or near the horizon, or when the eyes are protected by smoked glass. Spots have usually a short life, sometimes disappearing in a day or two,

sometimes lasting for a month or longer. The longest record is that of the spot seen during the years 1840–41 which persisted for eighteen months. Owing to the violent solar motion the changes in sun-spots are naturally very rapid, the disintegration of spots taking place usually by the formation of a bright " bridge " which may be shot across a spot at a high rate of speed (compared with terrestrial motions), of as much as one thousand miles per hour. The elevation of sun-spots with respect to the general photospheric level is still being actively discussed, even after the lapse of a century and a half since 1769, when Dr. A. Wilson of Glasgow first propounded his well-known theory, that the foreshortening of the penumbral filaments as the spot neared the sun's edge showed that the spots were saucer-like depressions in the sun's general surface. Spots having been seen which confirmed the theory while others seemed to disprove it, the arguments have gone on *pro* and *con.* For a more complete discussion, see Agnes M. Clerke, *Problems in Astrophysics.* In view of the very rapid change in gravitation near the surface of the sun already noted, it is altogether probable that the elevation at which sun-spots are formed is very little, if any, above the general level of the photosphere. The small allowable difference of altitude is not sufficient to permit the saucer-like sinks needed for Wilson's theory.

The most evident fact concerning the spots is their periodicity, first discovered in 1843 by Schwabe, the average period being 11.13 years. There are marked differences in the length from maximum to maximum, and equally great divergences in the intensity of the various maxima so that it must be said that spots are very irregular in their regularity. The individual periods range between 7.3 and 17.1 years as extremes. But no matter how divergent the period is from the mean, the rise to maximum spottedness always consumes less time than the descent to minimum. On the average the intervals are 4.62 years and 6.51 years, respectively. The sun-spot curve thus resembles the light curve of the average variable star of long period, and also those of the Cepheids. The importance of this fact is here

emphasized for the reason that we have learned from the researches of Abbot that the total radiation of the sun varies in amount, and as a consequence the sun must be regarded as a variable star of long period.

Various attempts have been made to examine the sun-spot curve by the methods of harmonic analysis in order to find any secondary periods that may underlie the main period of 11.13 years. The most notable attempts in recent years have been by Schuster,[1] Hirayama,[2] Kimura,[3] Michelson,[4] and Larmor and Yamaga.[5] Kimura and Michelson each examined 160 years of sun-spot records from 1750 to 1910, and although the material for examination was the same, the conclusions reached are greatly at variance. The former decides, "The 11-year period is not so conspicuous as generally considered. Although the most important of all, yet to my surprise there are a great many periodicities lying between 8 and 12 years, most of them being of considerable relative amplitude." Kimura predicts the form of the sun-spot curve up to the year 1950, the predictions giving a maximum of spots at the beginning of the year 1914, with an intensity about equivalent to that of the maximum of 1905–6. According to observations at Mt. Wilson, however, Nicholson[6] finds that the maximum did not take place until August, 1917, over three years later than the predicted time, while the activity was considerably greater than at the preceding maximum. Michelson concludes that "with the exception of the 11-year period and possibly a very long period (of the order of 100 years), the many periods found by previous investigations are illusory." Quite similar deductions are drawn by Larmor and Yamaga who even go so far as to state that when the periodic part is removed the residue of the sun-spot activity is of a fortuitous sporadic character, not amenable to further analysis. Various attempts have likewise been made to explain the sun-spots by means of the attractions of the

[1] *Phil. Trans. Roy. Soc.* 206.
[2] *Tokyo Sugata, 3,* 9.
[3] *M. N. R. A. S., 73,* 543.
[4] *Astrophysical Journal, 38,* 268.
[5] *Royal Soc. Proc. A., 93,* 493.
[6] *Publ. A. S. P., 31,* 223, 1919.

planets, particularly those of the giant of the sun's family. But Jupiter's period is 11.86 years, and even when other periods of other planets are superimposed, no success has followed the attempts to explain sun-spots by planetary influences. The cause of the cycle indeed seems as much unknown today as when a hundred years ago Schwabe first began his systematic observations.

Spots are never found more than 45° from the equator and seldom at the equator. A curious distribution of the spots in latitude manifests itself during the progress of the solar cycle. Approximately at the time of minimum, sun-spots begin to manifest themselves in two zones, more than 30° north and south of the equator. With the lapse of time, the spots are found closer and closer to the equator, the sun-spot maximum taking place with the spots in zones 17° north and south. The disturbance gradually dies out in latitude 8° or 10°, after a lapse of 13 or 14 years from the first outbreak. Before the final flickering out, the new cycle has begun to manifest itself, so that near sun-spot minimum there are found four zones of disturbance, two near the equator, and two farther north and south.

Many serious attempts have been made to connect sun-spots with various phenomena, solar and also terrestrial. The correlation with the solar manifestations mainly rests on secure ground, but with some of the earthly influences, the connection seems rather far-fetched. If it is hotter than the average at a certain locality in the United States, like St. Louis, or if mayhap at the same time, Northern France is having a cold spell, and if coincidently there is a large spot-group on the sun, an astronomer, or usually pseudo-astronomer, is always found who informs the daily press that the sun-spot is the cause of the heat (or cold). The famines in India, the potato crop in Ireland, the price of corn in England, the rain-fall in the Island of Mauritius, the financial panics of Wall Street all have been investigated by statistical methods, and each and all have been found to pass through periods of the same length, and to be connected with the sun-spot period. It has many times been said that "figures never lie." It is quite true that the figures themselves do not tell

falsehoods, but many and varied are the interpretations that may be placed on these figures. The president of every big business corporation well knows that if his company shows in two successive years the same approximate amount of earnings, it is very easy for him to declare a substantial dividend, or to charge certain amounts to "improvements," and curtail or even pass a dividend. The whole question depends on whether he wishes to please the fifty-one percent of the majority stock-holders (of whom he is one), or to take advantage of the forty-nine percent (of whom he is not one). It is quite possible, and indeed probable, that the weather and rainfall are connected with variations of solar activity as evidenced by sun-spots, and that other manifestations of meteorological changes are also correlated,—but to prove the connection "is another story." The weather is "not made on the spot," it depends on a vast variety of conditions and it is therefore difficult and well-nigh impossible to single out the solar cause from all of the possible influences that may affect the weather. It might not be out of place to remind all such investigators that a great variety of periods have been found in the sun-spot cycle itself, but that none of the subsidiary periods appear to have any reality, no matter how firmly substantiated by figures they seem to be. Most of the meteorological dependences seem to be equally illusory. There are, however, many terrestrial and many solar phenomena which have a well proven connection with sun-spots. These will be given below in brief form, though some of them will later be expanded more fully.

Records kept at the Greenwich Observatory and extending over nearly a hundred years, show (1), that the diurnal range of the magnetic declination, and (2), that the horizontal force of the magnetism flowing through the earth, follow the sun-spot fluctuations not only in the main 11-year period but even in the small and secondary variations. The parallelism is so intimate that it is at once evident that if the cause can be found of the sun-spot cycle there also will be found the true explanation of the variation of terrestrial magnetism. Although the records are not so complete, (3), aurorae and (4), magnetic storms are more abundant when spots are numerous. The same may be said (5), of faculae, and (6), of prominences. (7) The shape of the corona changes with the sun-spot period; at minimum of spots there are long equatorial extensions, and well defined polar rays. (8) The conclusions of Köppen, Stone, Gould, Nordmann, Newcomb, Abbot and Fowle, Arctowski and Bigelow are that there is a change in the mean temperature of the earth, small in size, but amounting to 0.7° between sun-spot maximum and minimum, the earth being cooler at sun-spot maximum, which, in fact, is quite contrary to the ordinary popular belief.

The contribution of the spectroscope regarding spots and related phenomena will be given in a subsequent chapter.

The state of our knowledge of the angular diameter of the sun is far from satisfactory. The accepted value of this fundamental quantity comes from measurements made many years ago with the heliometer. The discussion by Schurr and Ambronn gave the angular diameter of the sun when at its mean distance from the earth to be equal to 1920″.0 ± 0″.03. The investigations showed that there were slight but unmistakable differences between the polar and equatorial diameters, but in spite of these differences it was assumed that the sun was spherical. In this procedure they followed the example set by the great master, Auwers. In rediscussing the measures utilized by Schurr and Ambronn, Charles Lane Poor has come to the conclusion that the sun is not spherical but that it changes its shape with the progress of the sun-spot cycle. The changes in the diameter of the sun found by Poor were small, being of the order of 0″.1. The equatorial diameter of the sun appeared to be longer than the polar diameter at sun-spot maximum and shorter at sun-spot minimum. A further discussion by Poor of the measurements of solar photographs carried out under his direction at Columbia University confirmed the earlier conclusions on the heliometer measures.

In the present day of refinement in solar research it seems quite unsafe to assume that the sun is necessarily spherical or that the changes taking place in the polar and equatorial

diameters are so small that they are beyond the possibility of measurement. The heliometer, as the name signifies, was invented for the purpose of measuring the diameter of the sun, the first heliometer coming from the hands of Fraunhofer (p. 77). It is a very valuable and refined instrument of measurement, and in addition to its use on the sun it has been extensively employed in the determination of stellar parallaxes. The latter research has shown its limitations. When used on the sun, the great heat of the sun causes the same effect which is found in every instrument of precision when exposed to the sun's rays, namely, the instrument is put out of accurate adjustment. The heliometer being specially sensitive to changes in adjustment it is not surprising to find, by reference to the original observations, that the same observer using the same instrument on two successive days and under good observing conditions, would obtain differences in the measurement of the equatorial diameter of the sun amounting to 1″, 2″, 5″, or even 10″ or more. In addition, every observer has a "personal equation" in that he may constantly measure a quantity smaller or larger than the average observer. Each astronomer of skill who has ever made any visual measures with a telescope is familiar with the large and persistent values of personal equation when comparing measures made horizontally with those vertically.

The only practicable method of combining observations inconsistent among themselves is to group all the measures together and take the mean, at times assigning different weights. If the quantity of observations is sufficiently great and the number of observers numerous enough, it is quite safe to assume that the peculiarities of any one individual will have little effect in the final mean. For the determination of the diameter of the sun, Auwers had at his disposal no less than 15,000 observations made by 100 observers working between the years 1851 and 1883. The measures, however, were not all made by the heliometer.

The large personal errors to which these measures were subject have had a curious effect on all future observations, a parallel to which is not found in any other department of

THE 60-FOOT TOWER TELESCOPE AND THE SNOW HORIZONTAL TELESCOPE OF THE MT. WILSON OBSERVATORY

astronomical investigation. The result has virtually been to terminate all observational measures of the solar diameter. What would it avail any astronomer if he should measure the diameter of the sun with the heliometer on hundreds of days, spending perhaps many thousands of hours of diligent toil in the research, only to find that his results differed from the generally accepted value! To the astronomical world this difference would probably be regarded as a proof, not that the accepted value was in error or that the diameter of the sun was changing, but rather that the measures of the individual though made with the greatest of refinement were subject to personal equations. At best the astronomer secures little reward for the hard toil devoted to his skilled researches. Moreover, he is a human being and naturally he desires some compensation other than that of advertising to the rest of the scientific world that he is a faulty observer. And this, strange to relate, is the state of affairs in the enlightened days of the twentieth century when hundreds of thousands of dollars are spent each year in solar research! Astronomy appears to be virtually saying that no improvements are possible in the work done nearly half a century ago by the heliometer,— and so we shall assume that the sun is spherical and without change.

Are no other methods available? Why not try photography? Surely the great resources of modern astronomy can conquer any difficulties! There are indeed no difficulties of any note connected with the photographic processes, for excellent photographs of the sun are being secured daily. The main difficulty to be overcome is the same one that affects heliometer work, namely, the heat of the sun. This alters the length of the telescope tube and changes the focal length of the object glass so that the exact scale of the photographs is uncertain. These changes, however, do not alter the relative scales of the polar and equatorial diameters. Some indefatigable worker, therefore, has already waiting to his hand some hundreds of thousands of solar negatives to be measured and discussed for the purpose of determining whether or not the sun is spherical.

The only method apparently available of eliminating the

effect of the heat of the sun and at the same time applying photography is clearly outlined by Hayn[1] who applied it with great success at the eclipses of April 17, 1912, and August 21, 1914. By means of photographs taken at the time of a solar eclipse, not however, during totality, but during the partial phases, the shape and size of the sun can be determined, the shape and size of the moon also, and in addition, the times of contacts of the limbs of the sun and moon usually secured at eclipses. To attain successful measurements by this method great care must naturally be exercised to secure perfect photographs and especially to shield the telescope as much as possible from the direct rays of the sun. On its observational side the research presents no special difficulties, while on the theoretical side the problem is one of great simplicity, namely, that of finding the angular distance between the centers of two circles, one of the sun and one of the moon, at times recorded by the chronograph.

A research somewhat similar in character has been carried out by Henry Norris Russell[2] who measured photographs taken at Harvard College Observatory for the purpose of determining the position of the moon with respect to the stars. To secure satisfactory photographs, it was necessary to make the exposures on the moon the thousandth part of those required for the stars, and at the same time the telescopic object-glass had to be shielded from the light of the moon so that the photographic plate might not be fogged. The difficulties to be surmounted by Hayn's method during the progress of the eclipse are not as great as those overcome at Harvard in thus photographing the moon. To give information of the highest degree of reliability, it is necessary to know the latitude and longitude and the observed times with great precision. On this account it would be preferable to test Hayn's method at a fixed observatory rather than to attempt it under the temporary conditions of an eclipse expedition. The best locations will be those nearest the path of totality. At the eclipse of September 10, 1923, three

[1] *Astronomische Nachrichten, 201,* 185, 1915.
[2] *Harvard Annals, 72, 76* and *80.*

great American observatories and the Mexican National Observatory at Tacubaya will be conveniently located. The American institutions are Mount Wilson, Lick and Lowell observatories.

The determinations of the times of second and third contacts by Hayn's method is practically identical with that discussed briefly in Chapter IV. As a by-product of this method, the diameter of the moon is determined and also the irregularities of its profile. Naturally these quantities concerning the moon can be obtained more accurately by Russell's method of photographing at a time other than at an eclipse. The eclipse results on the moon will furnish a very valuable check on the accuracy and reliability of Hayn's method but the main advance will accrue from the application of photography to the difficult problem of determining the angular diameter of the sun.

CHAPTER VIII

MODERN ECLIPSES BEFORE 1878

"Tycho sought the truth
From that strange year in boyhood when he heard
The great eclipse foretold; and, on the day
Appointed, at the very minute even,
Beheld the weirdly punctual shadow creep
Across the sun, bewildering all the birds
With thoughts of evening." — NOYES.

ASTRONOMY owes much to the eclipse of the sun visible in Copenhagen on August 21, 1560, and to the fact that a red-headed, freckled-face boy of fourteen, destined to become the greatest and most careful of observational astronomers since the time of Hipparchus, had his keen young imagination fired by watching the "orange ember in the sky wane into smouldering ash." As a consequence, this boy, Tycho Brahe, resolved to devote his life to unravelling the deep mystery of these strange happenings. The romantic incidents of his productive life have been beautifully told by Alfred Noyes. From his own printing press in his observatory of Uranibourg appeared the *Historia Coelestis* in which appears a long list of eclipses beginning with one visible in Rome on March 28, in the year 5 A.D.

At the eclipse of May 3, 1715, Halley referred to that of the year 1140 as the last one previously observed in London. Although visible not far from London, Hind finds from investigation that this eclipse was not seen in the city itself, so that it can be said with certainty that not a single total eclipse of the sun had visited London for 600 years previous to 1715.

The first eclipse of the sun to be carefully observed in the British Colonies of America was that of June 24, 1778, which was watched by the astronomer David Rittenhouse

of Philadelphia. The first American expedition was organized and sent out from Harvard College for the eclipse of October 27, 1780. As this took place during the war of the American Revolution, an appeal was made to "the government of the Commonwealth that a vessel might be prepared to convey proper observers to Penobscot-Bay; and that application might be made to the officer who commanded the British garrison there, for leave to take a situation convenient for this purpose.

"Though involved in all the calamities and distresses of a severe war, the government discovered all the attention and readiness to promote the cause of science, which could have been expected in the most peaceable and prosperous times; and passed a resolve, directing the Board of War to fit out the Lincoln galley to convey me to Penobscot, or any other port at the eastward, with such assistants as I should judge necessary.

"Accordingly, I embarked October 9."[1]

Probably on account of an error in the tables, the eclipse was not total where the Harvard party was located. Between the first and second contacts Professor Williams measured the angular length of the moon subtended by the decreasing crescent of the sun. He gives the following description of what appeared shortly before the total phase was expected: "The sun's limb became so small as to appear like a circular thread or rather like a very fine horn. Both the ends lost their acuteness and seemed to break off in the form of small drops or stars some of which were round and others of an oblong figure. They would separate to a small distance, some would appear to run together again and then diminish until the whole disappeared."

Apparently this is a clear description of the so-called "Baily's Beads" observed by Francis Baily at the eclipse of 1836. An excellent description of this phenomenon is given by Agnes Clerke in her *History of Astronomy during the Nineteenth Century*, page 74. Baily gave the correct explanation of the phenomenon he saw as being due to irradiation. This same effect is seen when one holds up his

[1] *Memoirs American Academy of Arts and Sciences*, I, 84, 1783.

hand to the sunlight. In making the fingers come close together, they appear to touch each other before one feels they are actually in contact. An analogous manifestation is called the "black drop" which caused surprise at the transits of Venus in the years 1761 and 1769, and was the source of great trouble to astronomers at the transits of 1874 and 1882, so widely observed for the purpose of determining the solar parallax. The appearance of "Baily's Beads" is a phenomenon well worth watching and should be attentively looked for just before totality begins and just after it ends. Very excellent observations may be made with a good pair of field glasses or with a small telescope, a large telescope being unnecessary.

Baily was not an astronomer by profession. He was a stock-broker, and fortunately he had been successful in the making of money, with the result that he was able to devote the maturer years of his life to astronomy which he took up as his hobby. His work is but one of the many instances of the great debt of science to the amateur astronomer. One important result of his observations in 1836 was to show professional astronomers that at the time of the total eclipse of the sun there were other phenomena to observe than the mere times of contact of the limbs of the sun and moon.

The eclipse of 1836 witnessed not only the phenomenon of "Baily's Beads" but also an attempt by Forbes to test the physical constitution of the sun's atmosphere by means of the spectroscope. A new era for astronomy had accordingly dawned. An eclipse occurred in Southern Europe on July 8, 1842, and into the narrow track were collected the foremost astronomers from England, France, Germany and Russia. What was observed in 1836 was as nothing compared with the wonders of the eclipse of 1842!

One of the strangest portions of the history of astronomy before the middle of the nineteenth century is the evident lack of interest in, or perhaps one should say, the dearth of accurate observations of the phenomena visible at the time of a total eclipse of the sun. The startling suddenness of the apparition, coming in the early days of

DETAILS OF THE HYDROGEN PROMINENCES, JUNE 8, 1918, INCLUDING THE "EAGLE PROMINENCE."

In outline this prominence looks like an eagle alighting on the top of a cliff.

civilization without warning, must have brought terror to the hearts of the populace and caused them to fear war or pestilence or the death of a favorite prince. It is but natural that the prehistoric superstition of the dragon swallowing the sun should have spread during the middle ages from the far East to all of the civilized world. One fleeting glance, however, should have revealed, even to the most timorous minded, the pearly-gray light of the corona and brought to view the glow of the rosy-hued prominences. To those of the present generation, the nine hundred and ninety-nine out of a thousand who have never had the good fortune to witness a total solar eclipse, it might not be out of place to point out that a telescope is entirely unnecessary for viewing the beauties of the corona, this being a spectacle that derives its glory from the wide-spread splendor and slight gradations of contrast. A telescope, small or large will of course magnify any particular portion — but to see and enjoy the beauty of the corona as a whole nothing is actually needed but the normal naked eye.

Published references to the corona in the early literature are exceedingly rare. Plutarch and Philostratus give allusions which unmistakably refer to the corona, but apparently the first to take any scientific cognizance of the crown of glory was Kepler who seems to have witnessed the solar eclipse of 1605 in Naples. A hundred years later at the eclipse of 1706, Cassini, who was a practised observer, describes the "crown" of pale light, and he decides that it must be caused by the illumination of zodiacal light; and eleven years thereafter, Halley saw the corona and also prominences, but he was unable to decide whether the corona belonged to the sun or to the moon.

If so little attention was paid to the corona, it is not surprising that even less notice should be taken of the "red flames," though if one refers to the frontispiece he will see what a brilliant spectacle they afforded in the eclipse of 1918. The first reference to them seems to be at the eclipse of 1706 when they were apparently observed by Stannyan who wrote a description of them to Flamsteed. The first vivid portrayal was by Vassinius of Sweden who observed

them in 1733. The Spanish admiral Ulloa observed them while at sea during the eclipse of June 24, 1778, and he furnished a valuable account, with the added explanation that the rosy hues were caused by the sun's light shining through some hole or crevice in the limb of the moon!

The astronomers who witnessed the eclipse of 1842 were entirely unprepared for the phenomena that met their gaze. Baily repaired to Pavia, and made his observations from one of the rooms of the University. One of the professors, out of the goodness of his heart, offered to assist him in any way possible, but Baily informed him that all he wanted was to be " left *alone,* being persuaded that nothing is so injurious to the making of accurate observations, as the intrusion of unnecessary company." Not being content with this gentle hint, the key was taken from the outside of the door and it was securely locked on the inside. Baily's report of the observations made at the eclipse is found in the *Memoirs, R. A. S., 15,* 4, 1846, as follows: " The *beads* were distinctly visible. . . . I was astounded by a tremendous burst of applause from the streets below, and at the *same moment* was electrified at the sight of one of the most brilliant and splendid phenomena that can be imagined. For at that instant the dark body of the moon was *suddenly* surrounded with a *corona,* or kind of bright *glory.* . . . I had indeed anticipated a luminous circle round the moon during the time of total obscurity, but I did not expect, from any of the accounts of previous eclipses that I had read, to witness so magnificent an exhibition as that which took place. . . . The breadth of the corona, measured from the circumference of the moon, appeared to me to be nearly equal to half the moon's diameter. It had the appearance of brilliant rays. Its colour was quite white, not pearl colour, nor yellow, nor red.

" Splendid and astonishing, however, as this remarkable phenomenon really was, and although it could not fail to call forth the admiration and applause of every beholder, yet I must confess that there was at the same time something in its singular and wonderful appearance that was appalling. . . . But the most remarkable circumstance attending this phenomenon was the appearance of *three large protuberances* apparently emanating from the circumference of the moon, but evidently forming a portion of the corona. . . . All of these projections were of the same roseate cast of colour, and very distinct from the brilliant vivid white light that formed the corona. . . . The whole of these three protuberances were visible even to the last moment of total obscuration, at least, I never lost sight of them when looking in that direction; and when the first ray of light was admitted from the sun, they vanished with the corona, altogether, and day-light was instantly restored."

The same appearance was witnessed by Airy, by Arago and others. Arago has an interesting account of the effect of the eclipse on the populace who had gathered in great numbers to watch the phenomenon. " When the sun, reduced to a very narrow filament, began to throw upon the horizon only a very feeble light, a sort of uneasiness seized upon all; every one felt a desire to communicate his impressions to those around him. Hence arose a deep murmur, resembling that sent forth by the distant ocean after a tempest. The hum of voices increased in intensity as the solar crescent grew more slender; at length the crescent disappeared and an absolute silence marked this phase of the eclipse. The phenomenon in its magnificence had triumphed over the petulance of youth, over the levity which certain persons assume as a sign of superiority, over the noisy indifference of which soldiers usually make profession. A profound stillness also reigned in the air, the birds had ceased to sing."

The arrival of totality in Milan was greeted by a great shout, mingled with cries of " Long live the astronomers " who had provided such a beautiful phenomenon to please and interest the populace!

The unexpected nature of prominences and corona seen at the eclipse coupled with the publication in 1843 of Schwabe's discovery of the periodicity of sun-spots caused an unprecedented increase of interest in matters pertaining to the physical constitution of the sun. Various ingenious explanations appeared. While most astronomers believed

that the prominences were truly solar in their origin, there were many who thought they were possibly some exhalation in the earth's upper atmosphere, while still others believed that in some manner diffraction round the edge of the moon was responsible for these eclipse envelopes. In passing, we might mention a notion of no less an authority than Halley which was so curious that it should be classed along with William Herschel's belief that the sun might be cool and habitable. Halley[1] thought that the appearances on the eastern and western edges of the sun at a total eclipse might reasonably be expected to be different, for the reason that "the eastern limb of the moon had been exposed to the sun's rays for a fortnight, and as a consequence it would be natural to expect that the *heated lunar atmosphere* might exert some absorbing effect on the solar rays, while on the contrary the western edge of the moon being in darkness and cold for two weeks could exhibit no such absorbing action."

The interest aroused in total eclipses was now so great that astronomers were determined to take advantage of every opportunity, no matter how short the time of totality nor how great distances it was necessary to travel in order to view the eclipses. The eclipse of July 28, 1851, was visible in Norway and Sweden, and English astronomy was well represented in the persons of the astronomer royal Airy, Hind, Dawes, Carrington, Stephenson, Gray, Lassell and Williams. Although Faye[2] still asserted with force that the prominences were merely optical illusions or "mirages produced near the moon's surface," the general consensus of opinion was that the origin of the red flames was to be sought in the sun. To this fire of scarlet hue Airy gave the name of *sierra*.

Any lingering doubts regarding the origin of this sierra were forever dispelled by the observations made at the eclipse of July 18, 1860, visible in America, Spain and Northern Africa. The solution of the problem was accomplished by photography which was applied for the first time at an eclipse with anything like success. As the prominences

[1] *Phil. Trans.*, *29*, 248, 1715.
[2] *Memoirs, R. A. S.*, *21*, 5, 1853.

PROMINENCES PHOTOGRAPHED ON THE SUN WITHOUT AN ECLIPSE
by Slocum with 40-inch Yerkes Refractor.
The rapid changes appear to indicate horizontal currents.

are red in color to the eye and as the ordinary photographic plate is insensitive to red (plates are usually developed under ruby light) grave doubts were felt whether photographs would be able to portray the red flames. The only thing to do under the circumstances was to " try something and see what happens " (excellent advice for the scientist usually credited to the late Professor H. A. Rowland). Photography had already been applied at the eclipse of 1851 when Busch obtained some feeble impressions of the eclipsed sun by the daguerreotype process. Photography was even attempted in 1842 using iodized paper, but with no results. Warren de la Rue used the heliograph from Kew, enlarging the image before it reached the photographic plate, while Father Secchi employed a six-inch refractor without enlargement. Photographs of both observers were successful. De la Rue was near the Atlantic in Spain while Secchi was on the Mediterranean Coast, six minutes of elapsed time being necessary for the moon's shadow to travel from one station to the other. The conclusions from the 1860 eclipse were: 1. The prominences are rich in actinic power (now known to be due principally to the H and K light of calcium). 2. As the moon passed in front of the sun it progressively covered and uncovered the prominences, thereby demonstrating completely that their origin is strictly solar. 3. During the six minutes of elapsed time, changes were noted in some prominences but no variations in others. 4. The material from which the red flames arise is found around the whole solar globe. This is the *sierra* of Airy, but later, called the *chromosphere* by Lockyer.

The success attending the eclipse of 1860 came almost at the same time with the unraveling of the enigma of the spectrum. After two centuries of slow and painstaking progress, the crucial experiments had been performed by Kirchhoff by means of which the action of the spectroscope was at last understood. As a result, interest in eclipse observations was no longer confined to the astronomer alone, for many investigations were to be undertaken which were not confined by the determination of exact time or position. The birth of physical astronomy, or astrophysics, insured

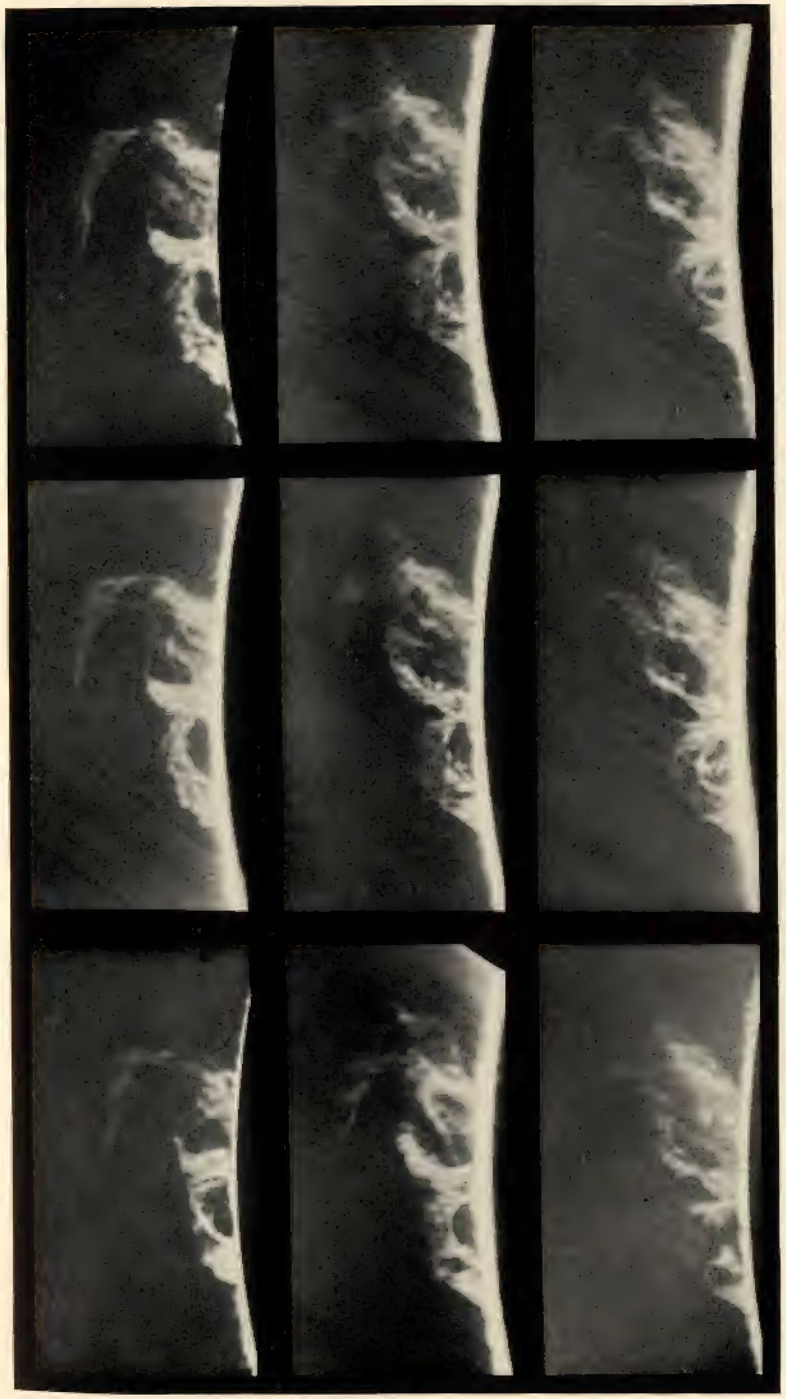
that henceforth eclipse observations would be of quite as much interest to the physicist as to the astronomer, and for the interpretation of these observations, research work in the laboratory was quite as important as that in the observatory. What spectrum would the prominences give? The answer was not difficult. Apparently the prominences were not, as had previously been thought, masses of photospheric material shot up to great heights by some explosive or volcanic action on the sun, since it was evident that the boomerang-shaped protuberance seen at the eclipse of 1851 could hardly have existed under the laws of gravitation. It was top-heavy and could not have hung there above the sun even for the short space of time it was visible if it had been composed of the general material forming the sun's photosphere. And then there was the distinct difference in color noted between the red flames and the body of the sun. Manifestly, since *all* of the gases forming the sun did not take part in the solar outburst, the prominences probably consisted of a few gases only, perhaps one of their chief constituents was the lightest of known gases, hydrogen, whose visible spectrum known from stellar investigations consisted of a strong line in the red, another in the blue, and a series of others coming closer together as the violet end of the spectrum was approached. The red line of hydrogen seemed to give a color not differing materially from the red of the prominences. If therefore the prominences were actually outbursts of hydrogen gas heated to great temperatures in the solar furnace, the eclipse spectrum would be vastly different from the ordinary solar spectrum. The band of light would not be continuous from the red to the violet end, nor would any dark Fraunhofer lines be visible. Since the prominences were probably gaseous, their spectrum, as known from the laws of Kirchhoff, must consist of bright lines on a dark background, an emission spectrum. It appeared therefore that the prominence spectrum would consist of a few bright lines only, the red and blue lines of hydrogen, and the series towards the more refrangible end, more difficult to see on account of the fact that the human eye is not sensitive to violet light.

But there was no eclipse on which to " try and see what happened " until August 18, 1868, so it was necessary for the physicists and astronomers to possess their souls with patience; but alas! the eclipse was visible only in far-off India, the Malay peninsula and Siam. The distances were great, but the problems were important, and accordingly several expeditions, two British, two French, one German and one Spanish were found in the eclipse track. The greatest success attended the observation of Janssen. The slit of his spectroscope directed to the edge of the sun revealed the spectrum of the prominences consisting, as had been thought, of a series of bright emission lines, most prominent among which were three lines, the red and the blue lines clearly belonging to hydrogen, but one of almost equal brilliancy in the yellow. The color of the yellow line seemed to match the D-lines of sodium, ever-present in laboratory experiments, but why should the gas sodium, comparatively heavy, be found in the prominences?

The brilliancy of the prominence lines was so remarkable that Janssen determined to seek them again after the eclipse was over. If they were solar in origin they must be found on the sun every day, varying it is true in shape and dimensions. The only reason why the prominences cannot be seen any day is the same reason why the stars are not visible in daylight, — the glare of the earth's atmosphere, especially when close to the sun, being very great. Abolish the atmosphere where the observer worked, and the stars and prominences would at once become visible; and since the moon has little or no appreciable atmosphere, the prominences would be seen each day without an eclipse to the " man in the moon " if such a person existed. But how get rid of, or diminish, the glare of the earth's atmosphere to such an extent that the prominence luminosity will be more intensive than the light of the earth's atmosphere? This feat can be accomplished by the spectroscope. The emission lines, C and F of hydrogen, found in prominences, are monochromatic in character, that is, these lines betake approximately the nature of mathematical lines and show no appreciable width. As a matter of fact, it is impossible to

diminish their intensity by increasing the dispersion of the spectroscope, whether this increase is accomplished by the addition of extra prisms or by the employment of a grating. Increased dispersion, however, spreads out these lines in the spectrum to greater distances apart, but their intensities are not thereby diminished. On the other hand, the continuous background of the solar spectrum can be weakened at will by merely increasing the amount of the dispersion, a fact which is at once evident since the light passing through the slit is by an increase of prisms spread over a greater area. Reflected sunlight, whether from the moon's surface, from the planets, from a silvered mirror or from particles of dust in the earth's atmosphere, gives the solar spectrum. Consequently, the prominences may be made visible by the spectroscope by the simple process of increasing the dispersion to such an extent that they can shine by contrast with the weakened atmospheric glare. As a result of these ideas, Janssen looked for and found the prominences after the eclipse was a thing of the past. The same or similar ideas had occurred to other workers with the spectroscope, notably to Huggins and to Lockyer in England. Without having been present at the eclipse, the latter tried for the prominences and found them for the first time on October 20, 1868. Lockyer sent a record of his observations to the French Academy, and without having heard of the Englishman's results, Janssen sent on to Paris the report of the work he had done at the eclipse and afterwards. By a strange coincidence, the papers from both investigators were read at the same sitting of the Academy, in honor of which event a medal was struck bearing the likeness of both Lockyer and Janssen.

Thus in the moment when the chemical nature of the prominences was discovered by the spectroscope, these objects ceased to be phenomena confined to eclipses only. As a happy and most fortunate result, a two-fold benefit thus accrued to the astronomer: freed from the necessity of observing prominences during the all too brief moments of a total eclipse he could devote his energies to other investiga-



Calcium Spectroheliograms of Solar Prominences on June 19, 1911
Photographs by Slocum. Sun's Diameter = 260 mm.

$2^h\ 18^m.2$ G.M.T. $3^h\ 4^m.3$ $3^h\ 12^m.5$
4 1.5 4 33.8 4 36.9
5 10.3 5 32.0 5 34.9

(This series is continued in the following plate)

CALCIUM SPECTROHELIOGRAMS OF SOLAR PROMINENCES ON JUNE 19, 1911
Photographs by Slocum. Sun's Diameter = 260 mm.

$5^h\ 58^m.3$ G.M.T. $7^h\ 39^m.5$ $7^h\ 50^m.3$
7 53.3 8 17.5 8 19.4
8 53.0 9 8.3 9 10.0

(This series is a continuation of that in the preceding plate)

tions. Not only could prominences be observed without an eclipse, but by the same methods, researches could be carried out on the solar envelope from which prominences arose, the chromosphere. Frequent violent eruptions on the sun carried the solar flames up to great distances and with enormous velocities, and these phenomena were observed visually by Young, Lockyer, Tacchini and a host of other investigators, many important researches[1] being carried out. The invention of the spectro-heliograph in 1893, independently and almost simultaneously, by Hale and Deslandres permitted an attack on these problems by the help of photography.

The great triumph of the spectroscope in 1868 gave evidence to the solar astronomer of the important problems awaiting solution, and it appeared almost certain that each observation carried out with care would be a valuable discovery. What was the corona? Did it shine by its own light, or by reflected sun's light? Was there any connection between the prominences and the corona? How far out did the corona extend, and were there any changes in its form that could be detected? Was the explanation of the dark Fraunhofer lines of the solar spectrum the true one, and was it possible that eclipses could help in the problem?

The eclipse of August 7, 1869, crossed America diagonally from Alaska to North Carolina. The United States government made a large appropriation to help defray the expenses, and as a result of this and also on account of the favorable time of year, the eclipse track in the United States was almost one continuous observatory, so thickly were the astronomers scattered. To give a list of those who saw the eclipse would be practically equivalent to making a record of every astronomer of any importance who was then living in the United States. Those too "were the good old days" before railroad executives were harassed by government regulations and Interstate Commerce Commissions and when free transportation for passengers and goods could be furnished. The following is copied from the *Report on Observations of the Total*

[1] See Young, *The Sun.*

Eclipse of the Sun, August 7, 1869. On page 3, J. H. C. Coffin, U. S. N., Superintendent of the Nautical Almanac, reports, "Col. Thomas A. Scott, vice-president of the Pennsylvania Central Railroad, furnished a special car, and with the cordial coöperation of Mr. Robert Harris, general superintendent of the Chicago, Burlington and Quincy, and Mr. C. E. Perkins of the Burlington and Missouri Railroad, provided free transportation for these parties, with all their instruments and apparatus to and from the places of observation. Free passes to ten or twelve others over the same routes were also granted." In the same report, page 115, Professor Morton estimates that "an expense of $1500 was spared the government appropriation."

Fortunately, clear skies greeted the observing parties. Little of the important work accomplished will be noted in detail here. Spectroscopically, the most valuable discovery was that the spectrum of the corona was continuous but was traversed by a single green ray. This green line was detected independently by both Harkness and Young, the latter identifying its position as coinciding with the line numbered 1474 on Kirchhoff's scale. But since this line 1474 is due to iron, it was surprising and perplexing in the highest degree to find it present in the corona and reaching such great heights above the sun's surface. In spite of the apparent coincidence, it was evident that the substance causing the green line was not iron. To it the name *coronium* was given, — and today after more than a half century of active research we know little more of coronium than when it was first discovered. At this same eclipse, Professor E. C. Pickering employed a portrait lens, thus recognizing its value in the portrayal of the heavens. As he was located at Mt. Pleasant, a little farther west than the rest of the expeditions, to him belongs the honor of securing the first successful photograph of the corona in America. Other photographs were secured by Winlock and others on a larger scale and with good definition which showed the corona and prominences.

The United States Congress appropriated the sum of $29,000 for observations at the eclipse of December 22,

1870, visible in Spain, Northern Africa, Sicily, Greece and Turkey. America was represented in the eclipse track by the following: Pierce, Newcomb, Harkness, Hall, Eastman, Winlock, Young, Langley, Pickering, Peters, Watson, Clark, Ernst, Willard, Ross, Gannet, and General Abbott. The British government granted £2000 and a ship. A great variety of observations were projected and only partially carried out on account of clouds that prevailed almost everywhere, observations photographic, spectroscopic, photometric and polariscopic. Lockyer met shipwreck and clouds, but was rewarded in the end by a glimpse of the corona for one brief second and a half! Janssen made good his exit from beleaguered Paris in a balloon, but though he succeeded in escaping from the bullets of the Germans, he was forced to capitulate to obscuration by the clouds.

The most conspicuous success awaited the efforts of Professor C. A. Young of Princeton who had foretold, and whose eye was the first to see the "*flash spectrum*." According to the theory of Kirchhoff (p. 97) the spectrum of the photosphere would be continuous from red to violet without any dark lines were it not for the overlying solar atmosphere. Here in the so-called *reversing layer*, the gases are at a lower temperature than in the photosphere, and on account of these cooler conditions the photospheric light is absorbed by the reversing layer, and the resultant spectrum is that of dark lines on a bright background. As already explained, if the photosphere could be removed, then the gases forming the reversing layer, since they are at a high temperature, would give a series of bright lines on a dark background, which is technically called a "reversal" of the Fraunhofer spectrum. To describe the appearance in 1870, one cannot do better than to quote from the words of the discoverer:[1] "The observation is possible only under peculiar circumstances. At a total eclipse of the sun, at the moment when the advancing moon has just covered the sun's disk, the solar atmosphere of course projects somewhat at the point where the last ray of sunlight has disappeared. If the spectro-

[1] Young, *The Sun*, p. 83.

scope be then adjusted with its slit tangent to the sun's image at the point of contact, a most beautiful phenomenon is seen. As the moon advances, making narrower and narrower the remaining sickle of the solar disk, the dark lines of the spectrum for the most part remain sensibly unchanged, though becoming somewhat more intense. A few, however, begin to fade out, and some even turn palely bright a minute or two before totality begins. But the moment the sun is hidden, through the whole length of the spectrum, in the red, the green, the violet, the bright lines flash out by hundreds and thousands, almost startlingly; as suddenly as stars from a bursting rockethead, and as evanescent, for the whole thing is over in two or three seconds. The layer seems to be only something under a thousand miles in thickness, and the moon's motion covers it very quickly.

"The phenomenon, though looked for at the first eclipses after solar spectroscopy began to be a science, was missed in 1868 and 1869, as the requisite adjustments are delicate, and was first actually observed only in 1870."

The same phenomenon was witnessed by Pye, a member of Young's party. The bright lines were so numerous that the impression was gained that every one of the thousands of Fraunhofer lines was reversed from dark to bright, while "the phenomenon was so sudden, so unexpected, and so wonderfully beautiful as to force an involuntary exclamation."[1] Professor Young called this sudden transition the *flash spectrum*. The same phenomenon was witnessed at the eclipse of December 12 of the following year by Maclear, Herschel, Lockyer and Fyers, the eclipse being total in India, Ceylon and Northern Australia (where clouds interfered). Again at the annular eclipse of June 6, 1872, seen by Pogson in India, and at the total eclipse of April 16, 1874, witnessed by Stone in South Africa, the flash spectrum was observed. This is one of the most interestingly beautiful and important of the phenomena connected with total eclipses. During the past half century the flash spectrum has been carefully observed at each eclipse. More

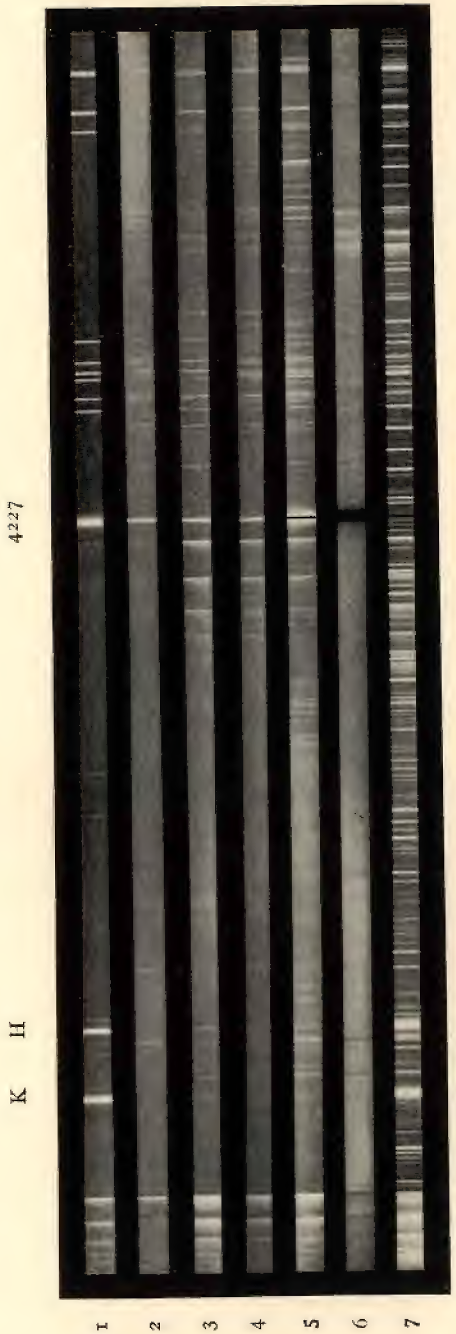
[1] *Memoirs, R. A. S., 41,* 435.

recently it has been photographed in exquisite detail, and has also been photographed at Mt. Wilson without an eclipse. (See Chapter XV.)

Apparently, it had been almost definitely settled that the corona is a truly solar appendage, for in addition to the spectroscopic evidence in the matter, the photographs in 1871 showed the same details in the coronal streamers from observing stations widely separated, an effect which could not possibly take place if the corona was terrestrial in origin. Such then was the state of scientific information regarding the corona as it existed *before* the eclipse of 1878 which was visible in America. Little was known with exactitude, there was very much of perplexity and uncertainty and doubt. The unsatisfactory nature of the whole subject may perhaps be envisaged in one sentence copied from a book by one of the most assiduous of spectroscopic investigators of the time, Norman Lockyer. "Now the whole phenomenon of the corona may be defined in two words, *cool prominences*."

If the knowledge of the corona was disappointing and perplexing, the decisions of the spectroscope regarding the reversing layer were equally uncertain. Kirchhoff's theory demanded that there should be a layer of vapors relatively cool surrounding the photosphere. Where was this layer, close to or far away from the sun? Was the layer thin, or one more extensive? At the eclipse of 1870, Young had discovered a flash spectrum apparently of thousands of lines suddenly turned from dark to bright. This phenomenon was visible for only two or three seconds at the beginning and ending of totality, and in consequence, the reversing layer must be very shallow, approximately 600 miles in thickness. But were *all* of the Fraunhofer lines turned from dark to bright? Since the appearance was visible during the few hurried and excited seconds of an eclipse, it was manifest that no exact comparison with Fraunhofer lines was possible, nor would be possible until the time should arrive when the flash spectrum could be recorded by photography. Moreover some spectral lines were seen to turn bright half a minute or more before the be-

ginning of totality, so that it was evident that not all of the reversing layer was confined to the 600-mile limit. Still other difficulties presented themselves. If the absorption did take place in a layer of the solar atmosphere, then the light of the photosphere passing tangentially through this layer at the sun's limb should experience an absorption greater in amount than that from the sun's center. In consequence, the spectra of the center and limb of the sun were compared in great detail, with the resulting discovery that any differences in the relative intensities of the lines were of such minor character that they could readily be explained by the slight darkening of the limb compared with that of the center. Kirchhoff believed that the spectral lines of any element like sodium were *characteristic*, or in other words, the same element gave always the same series of lines no matter how the element was vaporized. But when the flame spectrum was compared with that of the higher temperature of the electric arc, and the still greater temperature of the electric spark, great differences in the relative intensities of the lines were at once observed. Lockyer was the first to call attention to, and emphasize the importance of these changes. Take the element calcium, for instance. With a Bunsen flame and with small dispersion, the chief line visible is in the red end of the spectrum. At the temperature of the arc, the strongest line is in the blue, at 4226A. The red line is also visible and also two lines in the violet, the H and K lines of the solar spectrum. Increase the temperature of excitation by using the electric spark, and the two violet lines greatly increase their intensities and become much stronger than the blue line, while the red line practically disappears. Similar changes of intensity were found by Lockyer in magnesium, lithium, iron and other elements examined, and these conclusions have been abundantly verified by all observers since his time. Still further difficulties presented themselves. When the wave-lengths for the various metals were determined, it was discovered that different elements had spectral lines with apparently identical wave-lengths. It was found that some of these com-



The Spectrum of Calcium in the Arc and the Electric Furnace

Photographed at Mt. Wilson Observatory showing the effects of changing the temperature and quantity of vapor. Spectrum (1) is that of the electric arc. (2), (3) and (4) are spectra given by a small quantity of calcium in the furnace at different temperatures. (5) and (6) are at the same temperatures as (3) and (4) but with fifty times as much *Ca* vapor present. Note that H and K are much weaker than 4227, and that in (5) and (6) the latter is reversed.

mon lines were due to impurities in the metals examined, but when these lines were omitted from consideration there were still many lines evidently common to two or more elements. It was consequently manifest that the identification of lines in the solar spectrum was not the simple operation Kirchhoff supposed it to be, and that "the more observations were accumulated the more the spectroscopic difficulties increased."[1] Although some of the theories and conclusions of Lockyer were incorrect, nevertheless spectroscopists are under a great debt to him for the splendid series of researches carried out both in the laboratory and in the observatory.

To solve some of these difficulties, Lockyer busily investigated the spectra of many elements by his well-known method of *long and short lines*. If an electric arc is arranged horizontally and its image is projected on the vertical slit of the spectroscope, it is seen at once that the lengths of the lines in the spectrum vary considerably. Since the core of the vapor between the two carbon poles must be much hotter than that on the outside edges, it was evident to Lockyer that the short lines were high temperature lines that become visible only at the hottest point, that of the core, while the long lines were those which could exist at different temperatures, at the great heat of the center of the arc and at the lesser temperatures of the outside edges. This method of long and short lines thus appeared to give a ready and convenient means of separating the lines of highest temperature, which were comparatively few in number, from the balance of the spectrum.

By arranging the spectra of stars in an orderly series, beginning with the white stars, and passing through yellow stars to those red in color, it was noted by Lockyer that there was a steady increase in the total number of lines in the spectra, there being few lines in the white stars other than the hydrogen series, while the red stars possess an enormous number of spectral lines. Thus in the progression in the reverse direction, from red stars back to white, the spectra show fewer and fewer lines and become simpler

[1] Lockyer, *The Chemistry of the Sun*, p. 176.

in character. The same progression from red to white stars saw an increase in intensity in the H and K lines due to calcium. And as Lockyer was the first to recognize the importance of temperature in altering the character of spectra, so to him likewise belongs the great honor of recognizing that changes in stellar spectra show that the white stars are hotter than the yellow and these in turn are hotter than the red. (Present-day researches show that as the stars increase in temperature in the stellar series, the H and K lines do not steadily increase in intensity but reach a maximum strength, then begin to fade away and are entirely wanting in the hottest stars, the blue-white helium stars of spectral type B and stars of type O.)

Momentous in the highest degree therefore were the discoveries of Lockyer showing the importance of temperature in the interpretation of spectra, — but his explanations of the underlying causes have not borne the weight of time. His was the *dissociation theory* that the chemical atoms were continually broken up into elements less complex in structure, which exhibited simpler and simpler forms of spectra as higher and still higher temperatures were reached. As the white stars are those of the highest temperature, and as they show practically nothing but the spectrum of hydrogen which is the element of smallest atomic weight, it must represent the simplest element with the simplest spectrum. (The most recent researches show that though there may be dissociation of the chemical atoms this takes place in a manner vastly different from the dissociation demanded by Lockyer's theory).

The sun being but a typical yellow star, this theory can be put to the test in attempting to explain the phenomena of the solar atmosphere as revealed by eclipses. Lockyer assumed " that in the reversing layers of the sun and stars various degrees of *chemical dissociation* are at work, which dissociation prevents the coming together of the atoms which, at the temperature of the earth and at all artificial temperatures attained here, compose the metals, the metalloids and the compounds." [1] In consequence, there were grave doubts expressed by Lockyer whether the chemical elements known from laboratory experiments could at all exist at the great heat of the sun except in the cooler parts of its atmosphere. It was imagined by him that this atmosphere consisted of successive layers " like the skins of an onion," the layers next the sun obviously being the hottest. Hence in the interior layers could exist only " those constituents of the elementary bodies which can resist the greater heat of these regions." The spectrum of these inside layers, if such a spectrum could be obtained apart from that of the rest of the sun, would therefore not be a reversal of the Fraunhofer spectrum. According to Lockyer's hypothesis, the *whole* of the solar atmosphere is effective in the production of absorption. Young's observation of the flash spectrum demanded a shallow reversing layer of a few hundred miles, but Lockyer's theory refused to admit the existence of a reversing layer separate from the superincumbent strata. In other words, there could be no division possible into reversing layer, chromosphere and corona; these were but different manifestations of the solar atmosphere, the corona being regarded as the outermost and cooler parts of an atmosphere having a composite existence and obeying the laws of gravitation. In consequence of this theory, although Lockyer had himself witnessed the flash spectrum at the eclipse of 1871, he at first was forced to doubt, and then actually to deny the existence of the shallow reversing layer. The flashing out of lines that he observed " has been called the reversing layer; but I do not now (1881) believe that it is the reversing layer for a moment, for, when it comes to be examined, we shall probably find that scarcely any of the Fraunhofer lines owe their origin to it, and we shall have a spectrum which is not a counterpart of the solar spectrum." (*Loc. cit.* p. 360.) The solution of the problem could not be effected visually during the brief seconds available at a total eclipse for observation of the flash spectrum. The interpretation by one astronomer of what was observed should be entitled to as much weight as the opin-

[1] *The Chemistry of the Sun*, 201.

ion of another. There was no hope of a solution of the problem until the time should arrive when photography could come to the rescue by furnishing a permanent record of the flash spectrum which could be compared line by line with the Fraunhofer spectrum in order to see whether the one spectrum is the exact reversal of the other.

While these observations, epoch-making in their importance, were being made on prominences and reversing layer, the corona was not forgotten. Strange as it may now seem, there were still many astronomers of repute who believed that the origin of the coronal light should be sought, not in solar but in lunar or terrestrial causes. There were even two theories based on the moon, one that the corona was due to the diffraction of solar rays which pass near the moon's edge; the other, that the phenomenon was due to reflection of solar rays from the irregularities of the moon's surface. Another curious theory which found great favor at the time was that the corona was due simply to glare in the earth's atmosphere. As a result of this hypothesis the corona would necessarily be a phenomenon entirely local in its structural character, details appearing differently to observers at separate localities. If due simply to atmospheric glare, the coronal details should be found projected also on the dark moon.

There were now available four different methods for attacking the corona: first, visual observations by the naked eye, supplemented by the telescope; second, photography; third, polariscopic observations; and fourth, the spectroscope. The polariscope had already shown that part, at least, of the coronal light was reflected sunlight. This conclusion was corroborated by the discovery by Janssen at the eclipse of 1871 of dark Fraunhofer lines in the coronal spectrum, chief among which the D line of sodium was recognized. The green emission line discovered at the eclipse of 1869 was observed again in 1870 and 1871, Tennant in the latter year discovering that this ray was quite as conspicuous in a rift in the coronal light as in the adjacent streamers. The corona appeared thus to be shining from the luminosity of some unknown gas, which

strange to say shone as strongly in the dark regions of the corona as in the bright streamers.

In 1871 for the first time, and due to a suggestion by Young, a slitless spectroscope was tried. With the use of such an instrument at mid-totality, the emission lines appeared as *rings* of light, from the extent of which one could ascertain the height of the various gases forming the corona. By the help of photography in 1871, Lockyer showed that hydrogen extended uniformly about the sun to the enormous height of 200,000 miles. Could the solar atmosphere possibly extend to this colossal distance? Let us reason by analogy with what we know of the earth. Its atmosphere, as known from observations of meteors, extends about one hundred miles above sea-level. The sun is more than one hundred times the diameter of the earth and with the same relative distribution the solar atmosphere might conceivably extend 10,000 miles from the solar surface. But an atmosphere possesses mass and is obedient to the law of gravitation, and since gravity on the sun is twenty-seven times that on the earth, we would expect that a true atmosphere on the sun could not extend to elevations of more than 4,000 miles. But the hydrogen observed was at distances of 200,000 miles, with the green ring reaching the still greater extent of 300,000 miles, whereas the coronal streamers were seen to stretch out several millions of miles from the sun's surface. Apparently, the spectroscope had not solved many of the difficulties of the coronal structure, but rather had succeeded only in complicating matters, for to add to the difficulties already great, it was now necessary to explain how it was possible that the luminous gases hydrogen and coronium could extend to the very great distances revealed by the spectroscope. No terrestrial origin could be found for the green coronal line, nor did Young's discovery in 1876, that Kirchhoff's "1474" was a double line help solve the problem. The perplexities were indeed very great. A faint ray of hope appeared in an unexpected quarter. In 1866, shortly after the great November meteor shower, Schiaparelli proved that the Perseid meteors moved in the same path as Tuttle's comet of 1862, while the Leonids and the Temple

comet had identical orbits. This double coincidence between meteor and cometary orbits was corroborated in 1872 when it was found that the Andromedes, or Bielids as they are now called, had the same path about the sun as the lost Biela comet. The importance of meteors in any cosmical process was thus realized, and it was but natural that attempts should be made to solve the coronal puzzle by means of the meteoric hypothesis, — but as we shall see later, with little success. Newton and Cleveland Abbe in America and Lockyer in England pinned most faith to the meteoric explanations.

CHAPTER IX

NINETEENTH CENTURY ECLIPSES AFTER 1878

THE total eclipse of July 28, 1878, was observed in the United States from Wyoming to Texas. On account of the great interest in and the vast importance of the problems to be solved, the eclipse was widely observed from some twelve stations by about one hundred astronomers.

Ever since the discovery of the sun-spot period in 1843 and the finding that the earth's magnetism possessed the same period, astronomers had been on the alert to ascertain whether other solar phenomena moved in cycles parallel to the sun-spot curve. It had already been found that both prominences and faculae were more numerous when spots were great in number, and naturally the question was asked whether the coronal streamers did not originate with greater energy when spots were at a maximum. Here was an opportunity to test any conclusions, for Wolf's sun-spot number for July 1878 was 0.1, representing a minimum of spots, while the number for December 1870 was 135.4, a time of maximum of spots.

In the state of Colorado the moon's shadow path crossed the Rocky Mountains. Pike's Peak (altitude 14,400 feet) was occupied by Professor Langley and party. At their station before the day of the eclipse there was hail, rain, sleet, snow, fog and every form of bad weather which continued for a week, and to add to the discomforts, the horrors of mountain sickness had to be overcome. But on July 28, the weather conditions along the eclipse track were of the very best.

The first change noted in the corona of 1878 was the enormous decrease in total lustre, when compared with the coronas of 1870 and 1871, Harkness estimating the

luminosity to be only one-seventh of the corona of 1870, while Lockyer regarded 1878 to be one-tenth of the brightness of the 1871 eclipse. The decrease in brilliancy was accompanied by a remarkable and unexpected change in shape. To Janssen in 1871, the dark moon looked like the center of a giant dahlia, the corona being nearly circular in outline. In 1878, the streamers along the sun's axis were much shorter in length but much more pronounced in character, these polar rays resembling more than anything else the lines of force around a magnet. But the most astounding phenomenon was the enormous extent of the coronal streamers along the sun's equator. Langley in the pure, rare air of Pike's Peak followed these streamers to six diameters of the moon on one side, but on the other side where he had been more intently watching, to the colossal length of twelve diameters, or more than ten millions of miles! These equatorial extensions were confirmed by Simon Newcomb in Separation, Wyoming, by Cleveland Abbe farther down the slope of Pike's Peak, and by almost every astronomer who witnessed the eclipse. The perplexities surrounding the corona were accordingly multiplied many-fold, for how could a solar atmosphere obeying gravity exist at the huge distance of ten million miles from the sun's surface? Young and Abbe saw long faint beams shining along the sun's axis.

Remarkable as were the visual phenomena manifested, their testimony was no whit stranger than the revelations by means of the spectroscope. The hydrogen and green coronium emission lines were visible, but with such vastly diminished intensity compared with the eclipse of 1871 that most observers completely missed seeing them. They were, however, visible to Young, Eastman and some others. If the emission lines were weak, the Fraunhofer lines of the corona were comparatively strong, showing that the reflected light near the sun's limb was relatively stronger than in 1871, a fact confirmed by observations with the polariscope.

The eclipse of 1878 showed the long equatorial wings of the corona, strong polar brushes, faint incandescent light

of coronium and hydrogen, and light reflected strongly from material particles near the sun's limb. Were each of these four special features unalterably connected with the condition of the sun-spot minimum, or did they happen merely by chance? Time alone could furnish the answer. Great progress was made at this eclipse in the photography of the corona, particularly by the use of portrait lenses which were successful in portraying a mass of detail in the inner and brighter corona, but failed to show the outer streamers. Photographs of these faint extensions must needs wait until some date in the future when plates of greater sensitivity could be produced.

Another important observation at the eclipse of 1878 was the discovery (?) of two bright star-like objects by two American astronomers, Swift and Watson. The objects could not be identified with any of the fixed stars, and it was therefore necessarily assumed that they were small planets moving about the sun inside of the orbit of Mercury. The reputations of these two astronomers for careful observing were so great that it cost the science of astronomy a quarter of a century of eclipse observations before it was finally decided that no intra-Mercurial planets exist which are as large or as bright as the objects supposed to have been seen.

The next eclipse to be observed was that of May 17, 1882, the forerunner in the Saros of the eclipse of May 28, 1900. The 1882 eclipse was seen in Egypt with a brief duration of totality amounting to seventy-four seconds. This eclipse is memorable on account of the bright comet that was seen and photographed near the sun, the comet not being observed either before or after the eclipse. The photographic plates had now become more rapid, the dry plate having been invented, and accordingly the astronomers had to their hands better facilities for attacking the corona with camera and spectroscope. Also for the first time we hear of the prismatic camera, which is a slitless spectroscope, with a photographic plate to take the place of the observing eye-piece; and this instrument, particularly in the hands of Lockyer, was to play an important rôle

in eclipse spectroscopy. Eleven years having elapsed since 1871, the year 1882 was one of maximum sun-spots, there being no less than twenty-three separate spots on the face of the sun on the day before the eclipse. The form of the corona in no way resembled that of the minimum of 1878 but bore a striking resemblance to the crown of glory of 1871, the shape being more nearly rectangular, or even star-like, and the long equatorial extensions and strong polar brushes being entirely lacking. The spectroscope also revealed vast differences from the eclipse of 1878. The corona as a whole was more brilliant than that of the preceding eclipse, and the emission lines of the spectrum were obtained both by a slit spectroscope and by the prismatic camera. With the former instrument, Schuster photographed about thirty lines in the spectrum of the corona. Many new spectral lines were visible in the red and violet to Tacchini and Thollon respectively. These lines were seen and photographed during the progress of totality, and not near the beginning or end of the total phase. Apparently the lines did not seem to belong to the flash spectrum and must have their origin in the true corona. But for the first time a suspicion seems to have been aroused that the lines might after all be due to prominences and chromosphere and not to the true corona, for Schuster observed the H and K lines of calcium to appear bright even across the face of the dark moon where no light at all was supposed to exist! Evidently the chromospheric light was reflected by some atmosphere somewhere, either in the higher reaches of the sun's atmosphere directly in line with the center of the dark moon, or in the atmosphere of the earth. The first condition could hardly be possible and that left no contingency other than the second. Schuster's observation was not the first to reveal bright lines on the dark face of the moon because as early as 1870 Young had perceived bright hydrogen lines.

If the lines of emission were stronger in 1882 than in 1878, it was not so with the dark Fraunhofer lines. The spectroscopes revealed the continuous spectrum in the brighter inner corona, but farther from the sun the dark lines due to reflected photospheric light were observed both visually and in the photographs, but these lines were not so strong as in 1878. Sun-spot maximum appeared therefore to correspond to a star-like corona, with no polar brushes, strong coronium and other bright coronal lines, but with the Fraunhofer lines intrinsically weaker than at sun-spot minimum.

The direct photographs of the corona by Schuster were in better definition and showed more details than those of previous eclipses. In fact, the impressions made on the plates were so strong that Dr. Huggins obtained the idea that it might even be possible to photograph the corona without an eclipse. For observing the prominences without waiting for an eclipse, the spectroscope had already been utilized to get rid of the glare of the sunlight in our own atmosphere. It is not possible to make use of the spectroscope in the same manner for obtaining coronal photographs, for the simple reason that the bright-line radiations of coronium are not sufficiently strong in character to enable the coronium light to shine in contrast with the enfeebled solar glare. Many attempts to photograph the corona in full sunlight were made by a variety of different methods lasting over a number of years, the astronomers being urged on by great hopes since the first trial photographs seemed to predict success. The details of the early work of Huggins, and the later researches will be deferred until a subsequent chapter.

One-third of the way round the globe eastwards from the Dutch East Indies, where the eclipse of 1901, May 18, was observed, brings one to the middle of the Pacific Ocean. The eclipse track of May 6, 1883, lay almost entirely across the water, but fortunately, in its path there was a small coral reef, only seven miles long, and unknown ten years previously. The importance of the discoveries of 1882 and the fact that the eclipse of the year 1883 was of the very long duration of more than five minutes, attracted to Caroline Island, astronomers from America, England, France, Austria and Italy. The great risks taken by eclipse expeditions in the tropics of being overtaken by clouds was shown in this eclipse, but fortunately a clear spell between two

periods of clouds was experienced. The general features of the corona greatly resembled that of the year before, the sun continuing to show many spots. Owing to the long exposures possible, excellent photographs of the corona were secured, and for the first time in the history of eclipses, greater extensions of streamers were photographed than were visible to the eye.

The most important observations were unquestionably by means of the spectroscope. Up to this time, all observations during totality had shown a continuous spectrum of the corona close to the sun, and farther out faint Fraunhofer lines, with the bright green line of coronium crowning the whole. According to the dissociation theory of Lockyer, neither continuous spectrum nor dark lines could exist there, and "if these statements regarding the corona were strictly accurate my hypothesis was worthless."[1] Hence, a careful search was made by Janssen for Fraunhofer lines. They were found by him in great numbers, thus confirming the observation of 1882. To make assurance doubly sure, the dark spectrum lines in the corona were successfully photographed. As a result of these observations, Janssen concluded[2] that "the basis of the coronal spectrum was formed by the complete Fraunhofer spectrum, and that, therefore, there exists in the corona, and above all in certain localities of it, an enormous amount of reflected light; and since we know that the coronal atmosphere is very rare, it follows that these regions must abound in cosmic matter in the state of solid corpuscles, in order to explain the abundance of reflected sunlight."

Spectroscopic observations of great interest were made on the corona by Hastings. He used a 60° prism attached to a six-inch telescope, there being two totally reflecting prisms placed outside the slit so that the spectrum of two opposite sides of the sun could be brought together and examined by comparison. The observations were confined to the green coronium line. At the beginning of totality, this line was 12′ in length and very bright on the eastern

[1] Lockyer, *Chemistry of the Sun*, p. 365.
[2] *Comptes Rendus*, *92*, No. 10.

limb, while on the western limb it was only 4′ in length and comparatively faint. As the eclipse advanced, the inequality vanished, at mid-totality conditions were equal, while at the end of totality the lines on the western limb were the longer and brighter. Such a great change could not be explained by assuming that the moon in its motion progressively covered and uncovered the bright coronal radiations, and accordingly, Hastings attempted to explain his observations on the assumption that the outer corona has no real existence but that its appearance is caused by diffraction round the edge of the moon. On this hypothesis, the true corona is confined to a very narrow ring around the sun, the light from this inner ring of material substance being widened by diffraction to form the outer corona which thus takes upon itself all of the appearances of reality. To the astronomers who had seen the great extensions of 1878, it was hard to believe that diffraction of light could adequately explain the detail of the coronal streamers at the great distance of twelve diameters from the sun's limb, but it was equally difficult to understand how luminescence could exist in a solar atmosphere at the colossal distance of ten million miles from the sun's surface. If the coronal light were reflected, it could not be seen unless reflected from material particles, and if the light were intrinsic, how could it have any existence in an atmosphere so infinitesimally rare? The answer given by Hastings denied the solar origin of the corona, and seemed to be a step backward. Apparently there was no way out of the quandary, but to wait for future eclipses.

In the attempt to secure information regarding the flash spectrum three distinct improvements in the line of attack were inaugurated in 1882: 1. Eye observations were no longer to be trusted exclusively, the spectrum must be photographed. 2. A grating was used, before, during and after totality. 3. A moving plate was utilized with an integrating prism spectroscope to secure photographs before, during and after totality. The grating showed little in addition to the H and K lines seen near the limb throughout totality. The photographs attempting to secure the revers-

ing layer succeeded only in imprinting the hydrogen lines and comparatively few of the brighter lines, in fact the total number of lines were certainly too deficient to guarantee the confirmation of Young's belief that the whole Fraunhofer spectrum was reversed in the flash spectrum.

The total eclipse of August 29, 1886, was visible in the West Indies. The energies of many of the observers were devoted to testing the method of Huggins of photographing the corona without an eclipse. For this purpose, fifteen separate photographs were taken on the day before the eclipse and a series of twenty during the partial phases, these photographs to be compared with plates obtained during totality. The conclusions were quite definite, for not a single one of the coronal details was found on the plates taken outside of totality, and it seemed therefore necessary to decide that it was impossible to photograph the corona, except within the limits of a total eclipse, at least under the conditions of hazy sky and low sun that had prevailed.

Tacchini made a careful comparison of the prominences observed spectroscopically before and after totality with those seen directly during the total phase, and he concluded that all the prominences showed themselves larger and taller during an eclipse, the upper portions being white in color when the prominences exceeded 1′ of arc in height. The differences of apparent height may find a ready explanation in the effect of contrast with the background, inside and outside of totality, but the matter of the color of the prominences could not be so readily settled. For many years "white" prominences found a conspicuous place in spectroscopic literature. Tacchini observed the flash spectrum visually. Turner attempted to observe changes in the coronal streamers resembling currents, but obtained no results of value.

One of the expeditions at this eclipse experienced a series of accidents due to the unavoidable necessity of employing volunteer observers as assistants. Some of the incidents might have been amusing if an opportunity had been afforded on the morrow for making another attempt, — but

at the rare event of a total eclipse such untoward happenings are not laughing matters, but become almost tragedies. Some of these mishaps were: failure to get the sun's image on the photographic plate in the most important instrument, the breaking of the polar axis just before totality, in the next important instrument, the failure of an assistant to make exposures, the standing of two native policemen in front of the photometer during totality, the seizure of the plates by well-meaning but ill-advised customs officials, thereby causing a delay in the development of the plates until the following May by which time the plates had greatly deteriorated. Eclipse observers generally are not anxious to repeat such a chapter of accidents.

The eclipse of the following year, August 19, 1887, was one of widespread disappointment, for the projects so carefully prepared ended only in failure to secure results, not through any fault in the plans themselves but on account of the astronomer's enemy, clouds, which prevailed almost everywhere. Fine weather, due to holes in the cloudy sky, prevailed at several of the stations in Russia and Japan, however, and some photographs and observations of value were secured.

The year 1889 brought two eclipses, both extensively observed. Here was inaugurated the splendid series of expeditions sent out from the Lick Observatory. The path of the eclipse of January 1 crossed Nevada and California, and the photographers near the line of totality were so well organized for the work by Mr. Charles Burckhalter that an excellent series of photographs of the corona resulted. The best photograph secured at this eclipse, and in fact the very best obtained at any eclipse to this date, was secured by Barnard. The equipment was very meager. The largest lens employed was $3\frac{1}{2}$ inches aperture, stopped down to $1\frac{3}{4}$ inches, and of 49 inches focus. Barnard's success depended on an accurate adjustment of the instrument but more specially on the skill and care with which the plates were developed. Barnard was a professional photographer before he was an astronomer, and he was thoroughly familiar with the best methods of developing a plate in order to

bring forth all of the latent detail. The eclipse of December 22 of the same year was successfully photographed at Cayenne in the West Indies by the Lick party consisting of Burnham and Schaeberle. The photographs showed that changes had occurred in the corona since the eclipse of the beginning of the year. The earlier eclipse took place near sun-spot minimum and exhibited the equatorial extensions of the corona. The eclipse of December 22 is memorable from the death of Father Perry a few days after the eclipse, a martyr to the cause of science. This brave man, though greatly weakened, took part in the eclipse work, and having found as soon as totality passed that everything had passed off well, he called for three hearty British cheers, — which unfortunately he could not himself lead.

The greatest success attended the observations of April 16, 1893, largely through the use of apparatus much more powerful than had ever been employed before at an eclipse. The most conspicuous advance came to the party from the Lick Observatory in Chile who used a camera of five inches aperture and forty feet focus for securing photographs of the corona. Schaeberle decided to point the objective directly at the sun and to mount it on one fixed pier and the movable photographic plate on another, both piers to be wholly free from contact with the great tube extending between lens and plate. The slide carrying the photographic plate was the only moving part, and its motion was so regulated by means of inclined planes as to give it the same velocity and direction as the sun's focal image during the eclipse. The details of erecting this instrument, known as the Schaeberle mounting, are found in the *Contributions from the Lick Observatory, No. 4*. A careful focus was secured and beautiful photographs were obtained showing the prominences and inner corona with a definition which left little to be desired.

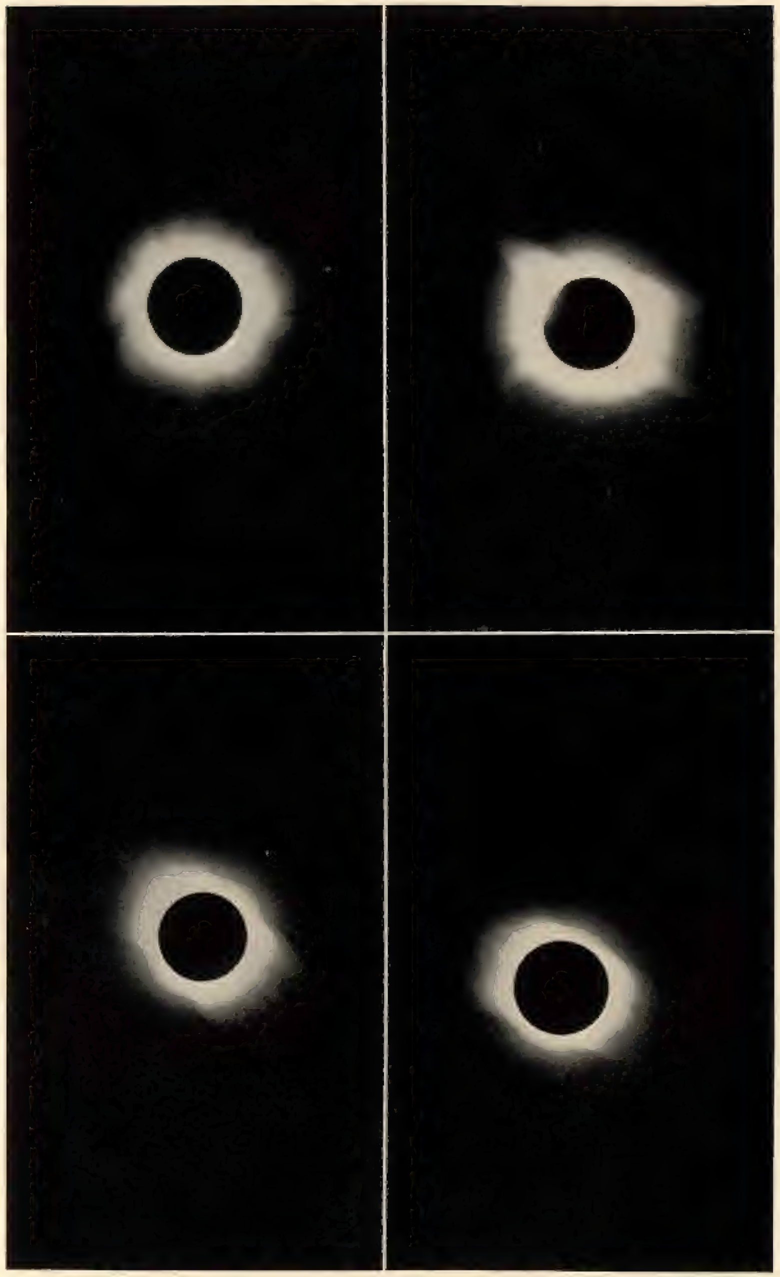
Optical power, up to then unprecedented, was employed in the prismatic camera designed by Lockyer and used by Fowler in West Africa. The camera had a focal length of 7 feet 6 inches with a prism of 45°, giving a dispersion of about two inches from F to K. Fowler secured photographs

1893
Chile

1898
India

1900
Georgia,
U. S. A.

1901
Sumatra



THE CORONA PHOTOGRAPHED BY LICK OBSERVATORY parties in different quarters of the world.

which were supplemented by a series obtained by Shackleton in Brazil, with the result that the positions of 164 chromospheric lines were measured between F and K. Deslandres, at the same eclipse, attempted to measure the rate of rotation of the corona by observing the relative displacement of the spectra of two regions of the corona at opposite sides of the sun placed in juxtaposition. A grating spectroscope was used, and the conclusion reached was that the corona partakes of the general rotation of the sun. Unfortunately, there is no justification for this deduction by Deslandres since the measures made by him were on the H and K lines which belong to the chromosphere and not to the corona. One of the most important results of this eclipse was that it became possible for the first time in eclipse spectroscopy to separate clearly the spectrum of the corona from that of the chromosphere, and it was henceforth no longer assumed that a spectral line visible during totality belonged of necessity to the corona.

The eclipse of 1896, taking place on August 9, was observed by a large number of expeditions. An English party consisting of Christie, Turner and Hills went to Japan where also was one from the Lick Observatory and another American expedition headed by Todd, and also two Japanese parties.

Lockyer went in H. M. S. *Volage* to Norway where a large party of seventy-five, including officers and sailors of the ship, took care of a large and varied program. In one department of the work, for instance, in the sketching of the corona, a competition was started on board ship by thirty-five volunteer sketchers, an artificial corona being exposed to view for 105 seconds, the time of duration of totality. Sixteen who showed the greatest proficiency were selected for sketching of the corona on eclipse day. But alas, for " the best laid schemes o' mice and men," — the clouds prevailed almost everywhere except where there was a small English party consisting of Stone and Shackleton. The latter was successful in timing his observations with the prismatic camera so well that the long desired photograph of the flash spectrum was at last secured. Although

the focus was not of the very finest, still there were shown a total of 464 lines in the spectrum between F and K. This photograph, taken by one of Lockyer's assistants, sounded the death-knell of the dissociation theory, — but Lockyer still refused to be convinced that the flash spectrum was a reversal of the Fraunhofer spectrum. His argument was a very simple one, which was, that between F and K, 5694 Fraunhofer lines were tabulated by Rowland, while in the eclipse spectra of 1893 there were but 164 lines and in 1896 but 464 lines, consequently showing but three and eight percent, respectively, of the Fraunhofer lines reversed in the flash spectrum. Lockyer however failed to draw attention to the fact that Rowland's atlas was secured with a much greater dispersion than that used at the eclipse and with vastly superior definition. Lockyer's conclusion,[1] the result of the spectra at these two eclipses, was that "the chromosphere is a region of high temperature in which there is a corresponding simplification of spectrum as compared with the cooler region in which the Fraunhofer absorption is produced." The manner of settling the question, the way of advancement for future eclipses was clearly indicated: the flash spectrum must again be photographed and with increased dispersion, and great care should be exercised to see that the exposures were made at the correct times, with as good focus and definition as possible.

Such photographs were secured at the eclipse of January 22, 1898, visible in India, where such excellent conditions of weather were experienced that then partially compensated for the ill luck of the previous eclipse. The largest expedition in point of numbers was that under the direction of Sir Norman Lockyer located at Viziadrug on the West Coast, the astronomers being assisted by the officers and men of H. M. S. *Melpomene*. The program was an extensive one, embracing visual and photographic observations of the corona, the most important problem being a spectroscopic attack on the chromosphere with two large prismatic cameras of six and nine inches aperture. By these two instruments about sixty photographs were secured, the exposure times

[1] *Recent and Coming Eclipses*, p. 111.

varying from 1 to 59 seconds. These included two series of ten snap-shots at the beginning and another ten at the end of totality and a number of exposures of different lengths during totality. Christie and Turner, representing the British Joint Permanent Eclipse Committee, were at Sahdol. Copeland was at Goglee, Newall and Hills were at Pulgaon, Campbell of the Lick-Crocker expedition was at Jeur, while at Talni was located Evershed and also Mr. and Mrs. Maunder.

The most important problem was that of the flash spectrum, and fortunately, successful photographs were secured by Fowler and Dr. Lockyer, by Campbell, by Hills, by Newall and by Evershed. A discussion of the spectra by Sir N. Lockyer again confirmed him in the opinion he had held since 1873, that many strong chromospheric lines were not represented among the Fraunhofer lines, while many of the dark lines found under ordinary conditions in the solar spectrum did not appear as bright lines in the flash spectrum. He therefore concluded that the flash did not represent the spectrum of the reversing layer. It is true that the hydrogen series and the helium lines of the flash spectrum are not found in the Fraunhofer spectrum, and also that there are great differences in intensity between the two spectra, and in a sense therefore one spectrum is not the exact reversal of the other; but none the less, it is impossible to reach any conclusion other than that practically every strong dark line in the solar spectrum is present as a bright line in the flash spectrum. The matter will be treated more fully in Chapter XIII, but it may be said here that the "reversing layer" is not a separate shell, lying close to the photosphere and inside of the chromosphere, but forms part of the chromosphere, being the lower and denser portions of it where, on account of its density, the chief Fraunhofer absorption takes place.

Exquisite photographs of the corona with the 40-foot camera were secured by Campbell, while Mrs. Maunder with a Dallmeyer lens of only one and a half inches aperture photographed the faint extensions of the corona running out to nearly six diameters from the moon's limb. The

corona of 1898 presented a mixed aspect, a combination of the polar brushes observable at sun-spot minimum being combined with the quadrilateral shape of sun-spot maximum.

One contribution of great importance was the measurement of the wave-length of the green coronium line. For nearly thirty years since its discovery, it had been assumed that the coronium line was identical in position with the chromospheric line at 5316.8 A. Lockyer, Fowler, Evershed and Campbell independently found the coronium line to be farther to the violet, at 5303 A. That the value of this wave-length was now found for the first time, in spite of observations made at several eclipses, will show more clearly than words can express that the eclipse spectra prior to 1898 were poor in definition and small in dispersion.

Newall used a spectrograph with two slits with which he hoped to secure photographs to test the rotation of the corona. Unfortunately, the slits were placed 8′ from the sun's limb and the coronal light was too feeble to impress any traces on the plate. Newall observed the corona with a polariscope while Turner attempted to achieve similar observations by photography.

A new epoch of accuracy in photographing the chromospheric spectrum having been begun in 1898, it was but natural that every effort should be made to continue the success of this work in 1900, in order to secure, if possible, still greater definition with larger dispersion. The eclipse track of May 28, 1900, lay over the southeastern part of the United States, and after crossing the Atlantic Ocean, passed over Portugal, Spain and Algeria. On account of its easy accessibility to American and European astronomers the eclipse was witnessed by a greater number of observers than ever before in the history of eclipses. Fortunately good weather was experienced almost everywhere. The program was a wide and varied one, and it will be possible here to mention only a few special lines of work and record the names of comparatively few of the many observers.

Photographs of the corona were taken in numbers to the hundreds, or even to the thousands, by small, medium,

THE CORONA
Photographed May 28, 1900 by E. E. Barnard and G. W. Ritchey.

large and huge sized cameras, the greatest focal length being that employed by the party from the Smithsonian Institution who utilized a lens of twelve inches aperture and 135 feet focal length. The photographs on this large scale were in good definition and they showed a great wealth of detail in the inner corona. Excellent photographs were secured at Wadesboro, N. C., by Professor Barnard and Mr. Ritchey with a horizontal camera of 61½ feet focus. A reproduction of the exposure of thirty seconds is given on page 165, and also a short exposure photograph on page 166, showing a fine group of prominences.

Both in America and in Europe, an extended attack was made on the flash spectrum by slit spectroscopes, by prismatic cameras and by gratings, plane and concave, used both with and without a slit. The United States Naval Observatory had three stations in the field, at Barnesville, Ga., at Griffin, Ga., and at Pinehurst, N. C. The three concave gratings used by Ames, Crew, and Humphreys were each employed with a slit. The photographs showed nothing. With plane grating and quartz lens, Huff secured a well-exposed spectrum, — but the focus was not of the very best. Better results were secured by Frost who used a concave grating, objectively without slit.

In Europe, Sir Norman Lockyer, located at Santa Pola in Spain, carried out an extended series of observations similar in scope to those made at Viziadrug in 1898. The nine-inch prism was combined with a camera 20 feet in focal length in order to secure a great linear dispersion in the resulting photographs for the purpose of measuring the heights of the various layers forming the sun's chromosphere. Successful photographs of the flash spectrum were secured by Fowler and Dr. Lockyer, and also by Dyson at Ovar, and Evershed at Mazapan in Algeria. The latter station was selected so that it might be as near as possible to the edge of the band of totality so that the photographs of the chromosphere might be obtained in high solar latitudes. Unfortunately, through an error in the *Nautical Almanac*, Evershed found himself just outside, instead of barely inside, the path of totality. The series of

photographs obtained, however, were of fine definition and were specially valuable in affording a means of comparison with photographs of the flash spectrum which have usually been taken near the solar equator. This comparison shows that the spectrum of the chromosphere is the same at the sun's polar regions as at low latitudes, and it appears fairly certain that the spectrum of the sun's limb is as constant in character as the ordinary Fraunhofer spectrum. In this connection it should be borne in mind that Evershed's photographs showed the flash spectrum where the moon was practically at grazing incidence with the sun, and consequently the layer of the chromosphere photographed must have been very close to the edge of the photosphere.

Fortunately, the Algiers Observatory was in the shadow track, and here through the kindness of the director, M. Trépeid, Mr. Wesley was given an opportunity to observe the corona visually with an equatorial coudé of 0.3 meters aperture. Mr. Wesley's long experience in the study of the corona had well fitted him for the task of finding out whether more detail could be observed visually than is portrayed on the best photographs. The conclusion reached was very definite that the photograph, if on a sufficiently large scale, exhibits all of the coronal features that can be seen with the eye.

Successful polariscopic observations were made by Turner, Newall, and others. The inner corona showed marked polarization, a result which was difficult to reconcile with the absence of Fraunhofer lines in the spectrum of the corona.

Interesting observations were made by Abbot with the bolometer in measuring the radiation of the corona at different distances from the sun's limb. Results of great value were secured, but they showed the necessity of confirming them by observations at succeeding eclipses.

Group of Prominences at Total Eclipse of May 28, 1900

Photographed with a horizontal telescope of 61½ feet focal length by E. E. Barnard and G. W. Ritchey.

CHAPTER X

PERSONAL EXPERIENCES IN 1900 AND 1901

THE first total eclipse witnessed by the author was that of May 28, 1900. The moon's shadow path in America traversed the southeastern states from New Orleans to Norfolk; it then crossed the Atlantic Ocean, passed over Spain and the Mediterranean and left the earth's surface at sunset in Northern Africa. Good weather conditions had been predicted on both sides of the Atlantic and so it was unnecessary for the European astronomers to travel to America or for the Americans to cross the Atlantic eastward in order to insure a promise of successful operations. A few astronomers, however, did make the sea journey. As an illustration of how little the average European knows about America — or rather it should be said, *did* know of the United States in the year 1900 — it can be said on good authority that before crossing the Atlantic to witness the eclipse, the head of one of the expeditions appealed to the United States government for a guard of soldiers to protect the lives of the party from the wild natives (sic) of North Carolina. On arriving in New York, however, the fears were effectually dispelled when the party found themselves aboard a luxurious Pennsylvania railroad train and discovered that they themselves, their baggage and their instruments were routed through to their destination, — and entirely free of charge.

In view of the accessibility of the eclipse track in the United States and on account of the fact that it was a very favorable season of the year for a trip to the South, it was but natural that such great American institutions as the Lick, Yerkes and Naval Observatories should send well-organized expeditions, and that individual astronomers should gather in great numbers to witness the fascinating

phenomenon. Most of the American astronomers were seeing their first eclipse and it might well have been thought that they would suffer from "nerves" at the exciting moments of totality; but there were many seasoned veterans in the ranks, men like Young, Langley and Campbell, who had witnessed eclipses in foreign lands.

Perhaps the most important part of the program for 1900 was the spectroscopic work. In 1896, after many trials, the first good photograph of the flash spectrum was obtained by Shackleton. In India in 1898, as a result of better definition, the spectrum photographs exhibited a wealth of detail that added greatly to our knowledge of solar physics. Evidently the procedure for the next eclipse should be the attempt to secure spectra with increased dispersion, so that wave-lengths should be determined with greater accuracy, thus permitting more reliable information regarding the sources of the spectral lines and rendering more positive our knowledge concerning motions of rotation of the solar envelopes. America is the home of the diffraction grating, plane and concave, brought to such perfection by the refined labors of Professor Henry A. Rowland of the Johns Hopkins University. As the eclipse was visible at such a comparatively short distance from Baltimore, the United States Naval Observatory invited a number of scientists who had had their training under Rowland and Ames, to become members of its expedition, among the number being the following: J. S. Ames, L. E. Jewell, R. W. Wood, W. J. Humphreys, Henry Crew, N. E. Dorsey, W. B. Huff, S. A. Mitchell, N. E. Gilbert, N. A. Kent, H. M. Reese and R. R. Tatnall. Among the more powerful instruments brought into service were three concave gratings, each used with slit, and two plane gratings each used objectively without slits. Each of these five gratings were employed in connection with a quartz lens. Ordinary photographic plates were used, and as these are but little sensitive to green, yellow and red light, it was decided to concentrate on the blue and violet parts of the spectrum; hence the employment of quartz, rather than glass, lenses. The concave gratings were mounted in the ordinary Rowland manner in the attempt

to secure sharp definition and large dispersion, — but the dispersion was too great for the light available and no lines were found on the photographs. Huff obtained well-exposed plates with a plane grating, but the focus was good for a short region only near wave-length 4000 A.

The experience gained in 1900 was put to use in the plans for the eclipse of the following year. On May 18, 1901, the moon's shadow touched the earth's surface at sunrise on the east coast of South Africa. After passing over the Island of Mauritius, the shadow traversed the Indian Ocean at cannonball speed and touched land shortly after noon on the west coast of the Island of Sumatra in the Dutch East Indies. After crossing over northern Borneo, Celebes and New Guinea, the shadow left the earth's surface at sunset far south of the Philippines. This eclipse was specially important on account of the very long duration of totality, six minutes. The location that afforded the best living conditions and promised the greatest success from favorable weather was the west coast of Sumatra, but such a site would carry the American astronomers as far away from home as they could possibly get, — half way round the world.

In view of this great duration of totality and the importance of the observations to be attempted, the United States government, through Congress, appropriated money to equip and send out an expedition of thirteen members, two from the Smithsonian Institution, six from the U. S. Naval Observatory, and five guests of the latter, all of whom had had eclipse experience in 1900, the author being one of the five guests. In order to arrive in the East Indies in plenty of time before the day of the eclipse, May 18, the expedition left San Francisco on February 16 on board the U. S. Army Transport *Sheridan, en route* to Manila. On the journey westward three delightful days were spent in Honolulu, viewing the points of interest of that far-off "Paradise of the Pacific." At that time the Hawaiian Islands were cut off from communication with the outside world, except in so far as news was brought by steamer, for there was no cable to Honolulu, — and it was before the days of wireless.

Eight days were spent in Manila in securing a vessel from the U. S. Navy Department and in having the heavy and cumbersome boxes containing the eclipse instruments transferred from the Army transport to the U. S. gunboat. In these eight days the members of the expedition had an excellent opportunity for seeing the capital of the islands which had then been for only three years in the hands of Uncle Sam. The two main characteristics of the Filipino that most impressed one were their love of — doing nothing, and their passion for gambling and cockfighting.

On March 26th, the U. S. S. *General Alava* left Manila to carry the expedition the remaining 2200 miles to the west coast of Sumatra where it was intended to locate for the purpose of the eclipse observations. After coasting along the Philippines and the north shore of Borneo, the equator was crossed on March 31st. Father Neptune came on board, and the reception to him was right royally given by the man-o'-war's men. April 2nd found us in the straits of Sunda which separate Java from Sumatra, and the ship passed within half a mile of the island volcano Krakatoa whose eruption in 1883 resulted in the loss of 40,000 lives. The huge tidal wave following the explosion, which inundated the whole surrounding country, left a Dutch man-of-war high and dry a mile and a quarter inland, and 76 feet above high water mark; and this wave was felt even in the English Channel, 11,000 miles away. The air wave sent out by the eruption was traced by barometers through seven complete circuits of the earth. Fine particles of dust were shot up to enormous distances in the atmosphere, causing the brilliant sunsets noticed for many months in 1883.

After coasting along the west of Sumatra, we entered the pretty little land-locked harbor of Emma Haven, probably the first American government ship that had ever entered port there, and were then at the end of our sea voyage of over 10,000 miles.

After official calls on the governor of that peaceful Dutch colony, we proceeded to Padang, the capital, just four miles distant, and obtained our first view of the island which was

The Pasig River at Manila

Krakatoa by its Eruption in 1883 Caused a Loss of 40,000 Lives

to be our home for the next two months. First impressions were formed at the Oranje Hotel, a typical hostelry of the East. The building, half hidden by cocoanut and tropical palms, is of one story with high thatched roof. At the front is the wide open verandah — the parlor and reception room of the hotel — and back of this, running through the middle of the building, is the dining room. On either side are the spacious bed rooms, each with its wide verandah, — exceedingly inviting places in the hot afternoons. The bed is the chief curiosity to the American, for it is a four-poster, with finely-figured mosquito net and of the huge dimensions of 7 x 8 feet. Over the mattress is spread a daintily embroidered sheet, but there are no bed-covers, — and indeed, under the equator, few blankets are needed. Of pillows, there are several, the ordinary bed having four and two "Dutch wives," — the name given to a long bolster used to keep the occupant of the bed cool.

A day in the East is begun by awaking about six o'clock. Coffee is immediately brought by the *jungus* — for no white man does any manual labor, and each has his native valet — and then, clad in pajamas, one risks the bath. Such a thing as a bath tub is unknown, the bath being taken in a cemented room with a cistern of water at the back, over the top of which is placed a wire screen to keep out inquisitive foreigners. Dipping water through a rectangular opening in the screen by means of a bucket, and throwing it over oneself, constitutes the bath, — and a very excellent one it proved to be. After leisurely dressing (for no one is ever in a hurry), a light breakfast is partaken of, consisting usually of bread and a few cold meats. The men come to breakfast dressed for the business of the morning, in their white suits, or often in their pajamas, consisting of trousers of cotton stuff of the most marvelous colors and patterns, and a coat or *kibaya* of white, made after the Chinese style without collar. But how tell of the dress of the ladies? For they appear at breakfast in costumes in which an American girl might be ashamed to be caught in her boudoir: a native skirt or *sarong* reaching to the ankles made of picturesque cotton stuff, and a lace-edged linen jacket. This is the dress

of the native women who wear neither shoes nor stockings. The Dutch women have adopted their costume *in toto*, except that they usually add a pair of gold embroidered slippers. After breakfast, the serious business of the day is taken up until it is time for the midday meal, or *rijsttafel*. This, as the name signifies, is largely made up of rice, — and it is a most astonishing meal. Into a large soup plate is put a liberal supply of splendidly cooked rice, and on top of this, chicken, meat, potatoes, and portions of fifteen or twenty curried dishes. It makes an astounding looking mess, but after a little experience in selecting the proper proportions and combinations of the curry and spices, the whole makes a very palatable dish. This is only the first course, to be followed by potatoes fried in cocoanut oil, and excellent chicken, with a third course of fruit. The next two hours of the day are universally given up to the siesta. About four o'clock, the East again awakes, and after a cup of tea or chocolate, takes another bath and dresses for the afternoon. The Dutchman seeks his club and plays a game of billiards or cards. Games requiring much exercise do not find favor in his eyes, but he has a taste for horse flesh, breeds most wonderful little ponies, and is always riding or driving. The ladies now appear for the first time during the day in European costume; and the hours before late dinner are given up to social functions. If these are of a ceremonious nature, the men must wear a black tail coat, and at least carry a hat, even if it is not worn.

A nice little informal gathering takes place before dinner each evening on the hotel verandah, where the men drink their *pitje* of gin and bitters, furnished by the hotel to all comers. Dinner at 8:30 or 9:00 has nothing remarkable about it, being very similar to our own. As soon as dinner is over, negligee is resumed, and the day is at an end.

Within a week there arrived in Padang two other parties besides our own from the United States, and scientists from England, Holland, France, Russia, Japan, and even India, about eighty astronomers altogether from all parts of the world, all bent on learning something about the sun.

They all had many interesting experiences in getting

A Cog-railroad and Tree Ferns in Sumatra

The Water Buffalo Takes His Daily Siesta

accustomed to East Indian ways. Perhaps one of the most amusing was the experience of one of the Englishmen at his first bath. Telling of it himself, he said, "I thought the cistern was the bath tub, and that it was the custom to keep it filled for the next occupant. But I could not make out what in the dickins the wire screen was doing there, so I pulled it off and crawled in. I didn't remain there long, however, for the Malays must have heard the great splashing of water and must have thought I was drowning, for they rushed in in great consternation, and ended my bath."

The Dutch were very kind and generous in their treatment of the foreign scientists, and did everything in their power to make the two months' stay in their island as easy in becoming acquainted with strange conditions and as enjoyable, as possible. Passes were furnished to each astronomer for passage over the "Staatsspoorweg op Sumatra," the railroad owned by the government which runs from Padang into the interior about 100 miles, one spur reaching Fort de Koek, the other Sawah Loento. These passes included not only the transportation of our persons, but also of freight and baggage, which is not carried free in the island. Labor was largely furnished without cost, machine shops were put at the disposal of the astronomers, and their slightest wish was readily met and generally anticipated. In short, these Hollanders were perfect models of hospitality.

In a few days after arrival, the astronomers had separated to the different locations determined on as bases of operations. The English divided into two parties, one going to Sawah Loento, where were located Mr. and Mrs. Newall, the other to an island off the coast of Sumatra where the party under Dyson could have the assistance of the officers and men of H. M. S. *Pigmy,* detailed there to help in the observations. The Dutch located not far from this island but on the mainland, and the astronomers had the help of the gunboat *Sumatra*. Perrine of the Lick Observatory of California decided on Padang as likely to be most favorable for his researches.

The Naval Observatory divided their party into three sections, and decided to locate along the line of the railroad.

The engineering principles under which this road was constructed were marvels of simplicity. If a small hill was met in laying out the line, the rails were laid over it, if the hill proved too steep for this, the tracks went around it. As the road starts from sea level and reaches an elevation of 4000 feet in less than 100 miles, following a valley between mountains of 9000 feet, there are many steep grades and sharp curves; in fact, for half the distance it becomes a cog road. But it is one of the most picturesque routes imaginable, running now through the green rice fields, now past fields ready for the sickle — for there are no seasons, and sowing, reaping, and threshing may be under way in the same field — now through a grove of cocoanut and banana palms, and again through a dense tropical jungle, where a dozen chattering monkeys scared up by the train go swinging away from limb to limb. On our first trip over the road we had just come to a bridge and were going down a steep grade when the Malay brakeman in some way lost his headgear. While we sat there for half a second wondering what he would do — for we had never seen a native without his *topi* — he solved the difficulty by jumping off the train, running back after his cap, and after a short run of 50 yards, catching the train again, which all this time was moving at its usual speed. At one of the stations where we got off for a few minutes to look around, we were immediately the center of a large crowd of most curious natives. They offered us bananas — *pisang* as they call them — and oranges, mostly green in color, little pieces of sugar-cane on slivers of wood, and many strange and wonderful looking messes. They eyed us with much wonder, and attempted a few words in Malay, which we however understood about as well as they did our English. In a few days however, they became acquainted with our mission, and spoke of us by the Dutch word "Zoneclips," while we, on the other hand, learned to make ourselves understood in Malay.

It was necessary to select the three Naval Observatory eclipse stations on the line of the railroad, on account of the difficulty of transporting heavy instruments and supplies into the interior. At Fort de Koch, near the edge of the

moon's shadow path, three members under the direction of Professor W. S. Eichelberger, U. S. N., investigated the corona and the atmosphere of the sun with photographic telescope and spectroscope. At Solok, the main station of the party was located under the direction of Professor A. N. Skinner, U. S. N. Here was Professor Barnard with a photographic telescope of 61½ ft. focus, which would give an image of the sun about seven inches in diameter. This celebrated astronomer had used this same instrument at the eclipse of 1900 at Wadesboro, N. C., and obtained, undoubtedly, the best photograph ever taken at an eclipse. In 1900, darkness lasted only about a minute and a half, but at the 1901 eclipse, this time was lengthened at Solok to nearly six minutes. As a result, Barnard decided to give a single exposure of two and a half minutes, on a plate 40 inches square, hoping thereby to obtain some exquisite details of the corona. At Solok were also located several spectroscopes under the supervision of Jewell who was engaged in various interesting objects of research.

Abbot of the Smithsonian Institution was investigating along two separate lines; first, with four telescopes mounted so as to photograph a large region in duplicate in the vicinity of the sun, he was attempting to discover new members of the solar system revolving inside of the orbit of the planet Mercury (if there be any such objects). His second task was a plan for measuring the heat of the corona and of the dark side of the moon turned towards us with the delicate bolometer, which is in reality nothing but a very sensitive thermometer capable of detecting the heat of an ordinary candle at the distance of five miles and of measuring differences of temperature to the one-millionth of a degree.

The author was in charge of the U. S. Naval Observatory party at Sawah Loento at the terminus of the government railroad. The *sawah,* or irrigated rice-field, is one of the prettiest sights imaginable. These fields are usually on the side of a hill, for the west coast of Sumatra, where the astronomers were located, is extremely rough and rugged. The sides of the hills have been terraced in order that the water may flow from one level to the one next lower, the

enormous amount of manual labor required to make these terraces being for the most part performed by the women. The rice grows under water, but artificial irrigation is not needed, for it rains almost every day, not merely a shower, but with an average fall of half an inch for every day of the year. A view of these rice terraces with their vivid tropical greens — and such brilliant color is never seen in the temperate zones — is certainly a magnificent sight. All trace of the *sawah,* however, has departed from the village of Sawah Loento, and its place has been taken by the Ombilian Coal mines, belonging to and operated by the Dutch government, which are remarkable for having a vein of rich coal forty feet in thickness.

The elevation of the railway station at Sawah Loento, according to the Dutch maps, is 262 meters above sea level, or 859 feet, The height of the eclipse station above this was measured by means of an aneroid barometer as 400 feet, which therefore made the elevation of the eclipse camp about 1,260 feet above sea level. A short distance away was the expedition from the Massachusetts Institute of Technology consisting of Burton, Hosmer, Harrison Smith and Matthes.

The solar problems to be investigated by the Naval Observatory party at Sawah Loento were along two separate lines: to photograph the corona with a camera 104 inches long, with lens six inches in diameter, and secondly, to photograph the spectrum of the chromosphere with a plane grating and quartz lens, used objectively without slit. To mount the instruments, piers of brick were constructed. Tents were used as coverings for the instruments, with an extra one for a storehouse, four tents altogether being set up. As the Boston party had reached Sawah Loento about ten days before us, they had learned to some extent the best way in which to proceed. The benefit of their experience was freely imparted, and much valuable information cheerfully given. To Meinheer van Lessen, the chief engineer of the coal mines, many thanks were due for the very generous way in which he looked after the supplying of all building material. The bricks, made near the coal mines,

A Sumatran Beauty

Market Scene in Sumatra

were transported to the eclipse location in three stages; first by rail to the residence of the controller; second, by the slow-moving "kreta kerbau," drawn by the sturdy water-buffalo; and third, for the remainder of the distance, about a third of a mile, by coolies. The slowness of the last part of the operation can perhaps be imagined when it is stated that in a basket slung on a bamboo pole on the shoulders of two coolies, five ordinary sized bricks would be carried. This was indeed the minimum load, but the maximum was never more than ten. It was very interesting to see six coolies, using three bamboo poles, carrying a barrel of cement. The coolies provided were convicts. The way in which the Dutch East Indies treat their prisoners is one of the interesting features in the management of the Malay. If a native of Sumatra commits a crime, he is sent to one of the other East India islands; and similarly natives of the other islands are sent to Sumatra to serve out the terms of their punishment. Consequently, in a penal settlement in Sumatra are natives of Java, Borneo, Celebes and of some of the smaller islands, but no Sumatrans. The reason for this strange separation is that there is great enmity between the different races, and so if a Javanese prisoner tries to escape he is immediately apprehended by the first Sumatran who meets him and sent back. And thus it is that there are large penal settlements with no surrounding walls and very few guards.

Such a settlement was at Sawah Loento. The convicts, to the number of 3,000, were employed in the coal mines. There was no guard over them except the "mandur" or policeman, one of themselves raised to a position of authority and responsibility, and answerable for the conduct of the coolies under him. Notwithstanding these conditions, one could go around with perfect safety and with less fear of molestation than in New York City. In fact, the pistols we had brought, with which to defend ourselves from cannibals, were soon packed carefully away in the bottom of our trunks.

In order to make the convicts more satisfied with their lot, the Dutch authorities paid them the amount of seven cents Dutch money, 2.8 cents American, per day. There

seemed to be a great amount of sickness among the convicts, possibly due to their confinement in the hot country, and several hundred of them were in hospitals or were put on sick duty without pay. These coolies were provided for us by the controller free of charge, and we were able to have about as many as we needed. They were very slow and not over fond of work, but nevertheless they could carry bricks about as fast as our Malay "tukang" could lay them. He used to squat at his work, and it took five days for him to lay 2,200 bricks. But the piers were finally built, the tents raised, and the instruments gradually mounted.

On May 7, the size of our party was doubled by the arrival of Mr. Rene Granger, of Georgia. He had arrived by P. & O. steamer, coming from the United States via Europe, to assist in the observations. He remained at Sawah Loento till after the eclipse and rendered very valuable help. To him was assigned the 104-inch camera, which was to be used in a horizontal position, receiving its light from a coelostat.

The day of the eclipse dawned clear, and our hopes were that these favorable conditions would remain until after totality, which occurred shortly after noon. First contact was observed in a perfectly clear sky, but soon after this, clouds began to gather, and a quarter of an hour before second contact the sky was completely overcast.

The disappearing crescent of the sun was observed with a binocular before one barrel of which was arranged a small plane grating in such a way that with one eye the spectrum could be seen, and with the other eye the sun itself. With this, shortly before the time of second contact, bright lines were seen for a few seconds at F and H and in several places in the green and yellow, but these disappeared almost at the instant of being seen, the sun being completely hidden by clouds, and the flash passed without our being able to see it.

Toward the middle of totality, conditions became a trifle better, so that it was possible to see, through clouds, the corona extending for about half a diameter from the sun, and with the small spectroscope to trace the form of the

coronium line quite distinctly. During no time of the $5^{m}\ 41^{s}$ of totality was an unclouded view of the corona obtained, but nevertheless, the clouds were so thin at the end of totality that the second flash was beautifully seen.

One hour after the total phase the clouds cleared away and a perfect sky remained for the rest of the day. Alas! that the eclipse did not occur at one o'clock instead of twelve!

The pre-arranged program was carried out, however, in its entirety as if it had been clear.

Powerful spectrographs were used also at the two other Naval Observatory stations. At the main station near Solok, Jewell had a concave grating, but as the result of the experience in 1900, the instrument was used without a slit. Dinwiddie had a prismatic camera under his care, a single large prism of 60° angle, kindly loaned by the Smithsonian Institution. Near the edge of the moon's shadow-path at Fort de Koch, Humphreys had a huge concave grating of nine inches aperture, with lines three inches in length and a radius of curvature of thirty feet. This was the largest grating ever ruled on Rowland's dividing engine and it was constructed specially for the purpose of this eclipse. It was not a perfect specimen of a grating for the diamond point had broken down during the course of the ruling. This station was purposely located near the edge of the shadow in order to photograph the low-lying layers of the chromosphere. Weather statistics did not promise favorable skies at Fort de Koch, — but strange to relate, it was the only locality in Sumatra where astronomers were stationed that clouds were not experienced. The main station at Solok was far from being fortunate, and the astronomers there succeeded in getting, — almost nothing, so dense were the clouds throughout the whole of totality.

From Jewell's many years at Johns Hopkins University, working as assistant to Rowland, he had had vast experience in the development of spectroscopic plates, and hence the task of developing the precious negatives secured was handed over to him. While this was being done, and while the instruments were being dismounted and boxed and

crated for their long journey home, we had some days to look around and observe the manners and customs of the people. The natives are all of them frightfully lazy — or shall we say only tired? — but it is the same disease that afflicts the natives all through the East. The Filipinos are troubled in the same manner, a similarity not to be wondered at, for Sumatrans and Filipinos both belong to the same great parent family. It was probably for this reason that the natives of the Dutch East Indies were so interesting.

The Malays belong to the so-called Mongolian division of mankind, and this is well illustrated by the strong resemblance between some of the higher types of each. The ordinary Malay is, of course, very different from the Chinaman, but in particular cases it is sometimes difficult to distinguish between them. The *jungus*, or servant of the author, so closely resembled a Chinaman, that it was difficult to believe that he had no Chinese blood in his veins. The Malays are of a light brown, or cinnamon complexion, and are rather small, the men being on the average three or four inches below the mean European height. The face is somewhat square, with high and prominent cheek bones; the expression often mild and not unpleasing; eyes black and slightly oblique; nose small but not flat; nostrils very dilated; mouth wide and large but not projecting; hands and feet small and delicate; legs very thin and weak; hair coarse, straight and black, but with weak and scanty beard which is invariably plucked out by the roots.

The Malay is naturally a man of easy-going, indolent character, who never gives open expression to a sense of astonishment or fear, and is probably little affected by these feelings. When alone, he is gloomy and taciturn, never either singing or talking to himself. The upper classes are exceedingly courteous, yet this outward refinement, strange to say, co-exists with the most pitiless cruelty and contempt of human life, traits which belong to the dark side of their character; and herein lies the explanation of the many diametrically opposed judgments which have been given us of the native of the East. There is another trait we must

Sumatran Mother and Half-caste Daughters

East Indians in Picturesque Garbs

not forget, and that is an insatiable love of gambling which no laws seem to be able to suppress.

These are the characteristics of the Malay, but they describe the Filipino just as accurately as they do the native of Sumatra. We were almost two months in Sumatra and in that time were thrown constantly with the natives who, as servants and coolies, were used continually. It became necessary to learn Malay and speak it; this however proved not to be a very difficult task as the language contains neither declensions nor conjugations.

The horned-roofed houses were very picturesque, and near Fort de Kock one of these was seen being modelled in gold and silver filigree work (at which the natives are very skillful), for a present from the colony to the Queen of Holland, to whom they are very loyal. The natives have a pretty legend, the *Menangkarbau,* about the origin of the horn-shaped roofs. This relates that there was once eternal enmity between the Javanese and Sumatrans, first one side conquering and then the other, and it seemed likely that the bloody conflict would continue without anything ever being decided. Finally the sages of the two peoples hit upon a plan to the effect that each nation should choose a champion from the animal world, that these should meet in mortal combat, and that whichever animal was victor, that nation was to be considered the conqueror for all time. The Javanese chose a vigorous young tiger, under the impression that their champion surely could not be beaten, while the forefathers of the Sumatran natives picked a strong two-year-old karibou bull. Fancy, if we can, the two tribes in half circles meeting to see the fray, the shouts of rejoicing on one side and the woes of the other when the karibou succeeds in using its horns to such advantage that the tiger is killed. To perpetuate this victory, the Sumatrans forever after build their roofs to show the karibou horns. Usually the roof has one pair of horns, but it may have two or three pairs, the extra pairs, we are told, signifying that a daughter is married in the house. For the family in Sumatra is maternal, with the mother as head of the house, so when a daughter is married she brings her husband

to live in her mother's home. Strange to relate, this form of family government co-exists with Mohammedanism where a man may have three or four wives. In such cases, however, we were never given to understand just how a man divided his time, and how he could live peaceably with so many mothers-in-law. The women do all the work, till the soil, gather the crops, thresh the rice and carry all the burdens, while the man evidently considers himself a superior being and succeeds in doing very little work. No wonder then he has three or four wives to work for him!

The Dutch have kept the original tribal relation and each tribe still has its chief, who is however, little more than a figurehead. Each man is required to perform one hundred days labor each year for the government, and as a great amount of this is put on the roads, excellent carriage roads appear even in almost inaccessible parts of the island. The principle under which the Dutch run their colonies has, by some writers, been described as merely for the purpose of making money out of them, and hence it has been the policy to keep the natives from becoming educated or Christianized, to keep out European immigrants and capitalists and to preserve the whole trade as a monopoly of the home government. And so we hear of the "culture system," but the products under the "system" have gradually been reduced, until now in Sumatra the chief ones are coffee and tobacco, — and who has not heard of "Sumatra wrappers"? Natives are obliged to plant a certain number of coffee trees each year, and sell the product at a fixed rate to the government. The Dutch have, however, been exceedingly successful in keeping the Malays docile and contented, and it might be well for the Americans to study the results of these three hundred years experiments on Malays of exactly the same characteristics as the Malays in the Philippines, the Filipinos.

After traveling half way round the world in search of knowledge, to have cloudy weather during the precious six minutes of the eclipse was indeed heart-rending, and the majority of the astronomers were pretty blue as a result. But when the plates came to be developed — and what a

boon the photographic plate has been to the astronomer! — it was found that the clouds had not interfered quite as much as expected. And so, down on the coast, the English and Dutch parties, with the assistance of the warships, succeeded in getting, with telescope and spectroscope, some really excellent photographs of the corona and "flash." The corona could not be traced a very great distance from the sun, but many exquisite details were seen in the inner corona. At Padang, Perrine of the Lick Observatory had the same kind of cloudy weather as experienced by nearly all the other scientists, yet the results of his work were very satisfactory in spite of the clouds. The photographs of the corona taken with the 40-foot photoheliograph, like those of the English and Dutch parties, showed splendid detail in the inner corona, but they were particularly interesting from an appearance in the northeasterly portion of the corona, as if an explosion had taken place. Perrine later found that this remarkable disturbance was immediately above the prominent and only sun-spot visible during eleven days, thus showing an intimate connection between sun-spots and disturbances in the sun.

The three parties at Sawah Loento suffered likewise from the clouds. The main work of Burton and his party from the Massachusetts Institute of Technology was investigating the magnetic disturbances while the eclipse was in progress; this work, however, could be carried out as well in cloudy weather as in clear. The Boston party found the disturbance not so great as at the eclipse of 1900. Newall of Cambridge, England, had a very complete spectroscopic program to carry out, including many interesting researches, among which was an attempt to measure the velocity of rotation of the corona and to see whether or not this halo shines by its own inherent light.

The few days previous to departure were spent at Padang where we had the pleasure of meeting many of the visiting astronomers whose accommodation taxed to the utmost the capacity of the leading hotels, the Oranje and the Atjeh. On the evening of May 27, the United States consular agent gave a dinner and farewell ball in honor of

the American astronomers and naval officers. Many prominent people were present, including Governor Joekes, also the officers of H. M. S. *Pygmy*. After the ball was over, the author slept in one of the beds of the Oranje Hotel with Professor Barnard, Dr. Abbot and one other. Our ship, the U. S. S. *General Alava*, had waited in Emma Haven to carry us back to Manila and we sailed at 10 A.M. May 28 on our homeward voyage. The eclipse of 1901 was a thing of the past! On June 8 we entered Manila Bay through the north channel, the Boca Chica, and anchored off Cavite. After a fortnight's wait in Manila, we sailed aboard the U. S. Army Transport *Indiana*, and reached San Francisco on July 16, five months from the day we had departed.

What scientific results had been obtained from the long journey and the many months spent away from regular duties? When the photographic plates were studied in detail it was found that much of great value had been secured in spite of the clouds, and as a result the Sumatra eclipse had contributed some very important information regarding the problems of solar physics.

Filipino Homes Built on Stilts to Get Out of the Wet

Horn-shaped Roofs and Handsome Wood-carving in Sumatra

CHAPTER XI

THE SPANISH ECLIPSE OF 1905

THE next eclipse to be widely observed was that of August 30, 1905. On this day the eclipse began in Manitoba and after crossing through Northern Canada, it left Labrador about 8 A.M. on its trip across the Atlantic. Shortly after noon the shadow cut into Spain, then on through the Mediterranean, Northern Africa and Egypt, leaving the earth's surface at sunset on the coast of the Indian Ocean.

Spain was chosen by the majority of astronomers, both because the duration of totality was longer, and because the promise of good weather conditions was better; and here in a path one hundred and twenty miles in width running diagonally across the peninsula, hundreds of astronomers, American and European, were gathered.

The party sent out by the United States government was under the general direction of Rear-Admiral Colby M. Chester, U. S. N., superintendent of the Naval Observatory. Three men-of-war were furnished by the Navy Department for the purposes of the expedition, the U. S. S. *Minneapolis*, U. S. S. *Dixie* and U. S. S. *Caesar*, the first named being the flagship of the squadron.

The three vessels left separately from the United States about the end of June and met in Gibraltar about the middle of July. " Gib " is one of the most interesting places in the world, especially when entering on a naval vessel. It was a glorious sight, as we steamed in at dawn on board the *Minneapolis*, to behold the wonderful rock, and sheltered at its base, the Mediterranean squadron of the British navy, consisting of eight battleships and eight first-class cruisers, under the greatest of English admirals of the time, Lord Charles Beresford. The morning of our arrival was spent

in firing and acknowledging thunderous salutes, and in making official calls. To carry out properly these acts of courtesy between the American and British nations, it was necessary to fire no less than one hundred and fifty-two rounds of ammunition. On the morning of our second day in Gibraltar, the British squadron sailed, and it gave us an idea of the quality of the greatest navy in the world to see the splendid, seamanlike manner in which the big ships got under way without confusion, and one by one in perfect order departed from the crowded harbor.

Gibraltar covers only about two square miles, so it did not take much time for us to take in all the sights of the streets with their motley population of English, Spanish and Moors, and to visit the places of historical interest. The "Key of the Mediterranean" stretches from north to south with a length of three miles and a breadth of little more than half a mile. The north and east sides of the "rock" are almost vertical, while to the south and west it descends in step-like terraces, and thus only a small portion of the area is habitable. From the foot of Mt. Rockgun (1,356 feet) the land stretches northward towards Spain in a low-lying flat isthmus not more than half a mile in width. The central portion of this, a third of a mile in width, is kept as a neutral zone between the Spanish and British possessions, and is lined with sentry boxes on either side. The fortifications of the side towards Spain consist mainly in galleries hollowed out in the face of Rockgun during the four years' siege ending in 1783. Signal Station (1,295 feet) and Highest Point (1,396 feet) are surmounted with great guns which defend the twelve miles of strait that flow between Europa point and Africa.

After leaving Gibraltar and entering the blue waters of the Mediterranean, the *Minneapolis* steamed along the coast of Spain for about four hundred miles and anchored in the harbor of Valencia, the first American man-of-war to visit a Spanish port since the Spanish-American War.

At Valencia, the home of the Cid, the annual fair was in progress, and the chief attraction was the bull fight. During the eight days of the fair, five *Corridas de toros*

were held. Six bulls were killed at four of these fights, and in the other, "extra-special" fight, eight bulls were slaughtered. Those of us who went to the first of these disgusting spectacles saw six bulls and nineteen horses butchered, and it is hardly necessary to remark that we did not go a second time.

The bull ring is of the shape that the name signifies, the one in Valencia being one of the largest in Spain, capable of holding 17,000 people. The fight is opened by a procession into the ring of those taking part. At the head of the procession walk the *espadas*, then come the *banderilleros*, the mounted *picadores* and the attendants (*chulos*) on foot with a team of gaily bedecked mules used in dragging off the dead horses and bulls. The fight can be described as follows:

It is composed of three acts. In the first act the *picadores* receive the charge of the bull, which they try to withstand by prodding him with their pikes. In nearly every case horse and rider are overthrown by the bull and the horse terribly gored. The bull's attention is attracted as quickly as possible by the waving of cloaks in the hands of attendants and he is enticed to leave the prostrate man and horse. This performance is repeated several times until the bull becomes a little wearied. The second act now begins, and in this a *banderillero* on foot will meet the bull in full charge, stick into his neck on either side two barbed darts about thirty inches long covered with colored paper, and step nimbly aside to escape the enraged animal. Usually eight of these darts are used. In the third and last act, the *espada* teases the bull with his red cloth and manoeuvers to get the weakened bull in a favorable position to give the death stroke by thrusting his sword through the neck and into the bull's heart. Great is the applause when the bull falls dead from a single stroke. The dead bull and horses are dragged out by the mule team, the ring is sanded to cover up all traces of blood, a new bull is let in and the fight goes on as before. (A bull fight is quite expensive. Each bull costs about $250, and horses, though poor, cost

something. The animals killed in the ordinary *corrida* are worth at least $2,000.)

It had been decided to divide the Naval Observatory expedition into three, sending two parties to Spain and one to Africa. The U. S. S. *Dixie* took the African party to Tunis, and the astronomers Jewell, Gilbert and Dinwiddie located themselves at Guelma near the central line of the shadow cast by the moon. In Spain there were two parties, one located at the edge of the path of totality at Puerto Coeli, and the other near the central line at Daroca. At the former place were Lieutenant Commander Hayden, Professor Littell, Mr. Peters and Mr. Hill from the Naval Observatory and Mr. Anderson from the Johns Hopkins University; at the latter place were stationed Professor Eichelberger and Mr. Yowell of the U. S. Naval Observatory, Professor Bigelow of the U. S. Weather Bureau, Mr. Hoxton, Mr. Olivier and myself.

Daroca is in the heart of old Spain, about forty miles from Saragossa, and as a railroad had been there only four years it was a *terra incognita* for modern tourists — for which we were duly thankful. Our six weeks' stay there was a happy commingling of hard work — and there was plenty of work to do — with pleasant experiences in getting acquainted with Spanish life and people. The site for the town is indeed a peculiar one, in a valley so surrounded by hills that each heavy rain storm used to flood the city, until about 1600, a tunnel was constructed through one of the hills to carry away the waters. The tops of these hills are crowned with walls and forts, most of them constructed by the Moors a thousand years ago, some of them by the Catholic Spanish since that time. There is one tower of special interest, and still in good state of preservation, which is said to have been built by the Romans before Saguntum was founded, and it is, therefore, more than two thousand years old. (The railroad from Valencia passes through Saguntum where Hannibal and the Romans had their memorable fight in B.C. 238.)

The Spaniards received us with open arms and did everything in their power to assist in our work and to make our

THE CITADEL CROWNING THE CITY OF DAROCA

AN OLD AQUEDUCT AT DAROCA, STILL IN USE. LOOKING SOUTH TO THE VALLEY

stay in their midst as pleasant as possible. As no one in the place could speak English, it was necessary to make ourselves understood in their language. They did not laugh at our mistakes in grammer or pronunciation, as we might have done in their places, but were always and at all times the souls of politeness and courtesy.

To help in the erection of the temporary observatory, six sailors were sent in from the *Minneapolis,* and all hands, astronomers and sailors, worked each day from early morning till late at night, building piers, erecting telescopes with houses to shelter them, mounting spectroscopes, and fixing up a meteorological observatory. After the carpenters and machinists had finished their work of construction, it was necessary for the scientists to focus and adjust, to see that everything was in good working order, and to make trial photographs. A few days before the eclipse, the party was increased in size to thirty-five, officers and sailors having come up from the ship for the purpose of assisting in the observations. Frequent drills were held in order to familiarize each one with his part and thus to be sure that everything would go right and that no precious seconds would be wasted at the time of eclipse.

The location of the eclipse camp was half a mile south of the town, in the midst of a beautiful, fertile valley. From there, while we worked, we could catch glimpses of scenery typical of Spain. The first feature to attract one's attention is the extremely barren aspect of the country, which is in sharp contrast with the garden-like appearance of England. The hills of Spain were in early times densely wooded, but now are almost entirely devoid of trees and look from a distance as if there were not a particle of vegetation on them. Moreover, the rainfall is so slight that agricultural pursuits must rely upon irrigation, and thus it is only the valleys that are green and cultivated. In such a valley along the shores of the little river was our eclipse camp located. The greenest field was decided upon as the site of the observatory, and upon application to its owner for permission we found that he was quite satisfied to allow his plot of ground to be used, but thought some compensa-

tion should be made for the valuable crop of grass that might possibly be raised during the summer. On receipt of one hundred pesetas, he forthwith proceeded to take a fatherly interest in all of our doings, and explained scientific matters to every one as if he had been chief of the expedition. His field became the center of interest in the community, and people came from all sides to look upon the strange doings. As a prominent trait of the Spanish peasant seems to be a great and overpowering curiosity, we had plenty of onlookers; and when the mayor and a few of the most prominent citizens were invited to look at the moon through our five-inch telescope, we were rather surprised — to put it mildly — to find over one hundred people turn up, when only a half score had been invited. Their curiosity took the form only of making each and every one in the town intensely interested in what was going on, and to show that interest they turned out in force each afternoon to see how matters were progressing. It might be asked, what their attitude was towards these Americans who had so lately beaten them in the small war. Before the expeditions reached Spain, it was feared that perhaps there might be some friction on that account, but these fears were not realized. As a matter of fact, the only person we met who seemed to have any feeling at all in the matter was a former soldier in the Spanish army. He had seen service in the Philippines, had been captured and thrust into prison by the Filipinos, had been rescued by the Americans, and as a result he had only the kindest feelings towards everything belonging to the United States. As for the rest of the people, they seemed to have forgotten all about it, or else they did not know there had been a war, for it must not be forgotten that only about one quarter of the people in Spain can read and write.

After this my third total eclipse, I can confidently say that observations at such a time consist of much hard work and many nerve-racking experiences. The astronomer is never on hand sufficiently long beforehand to take things quietly and easily, he must work under conditions to which he is totally unused, and over his head hangs the knowledge

that everything must be completed by a certain day and a certain hour, for the eclipse cannot be postponed, and there is no second trial in case of failure. In addition to working hard all day as carpenter and instrument maker, the astronomer must stay up half the night adjusting his instruments on stars, so that during the last few days before the eclipse very few hours of sleep each night are obtained. However, in spite of the many difficulties that were continually cropping up, the mounting and adjusting of the instruments was practically completed by August 25, when our observing party was swelled in numbers by the officers and men from the *Minneapolis*. From then until eclipse day the time was spent in putting the finishing touches on the work of adjustment, and in having frequent drills in order to insure that everything would go without a hitch.

What was the promise of weather for the important day? We had been closely scrutinizing the weather each day to see what conditions we were to expect, and were much pleased to find that the sky was usually clear just after noon, the hour when the eclipse was to occur. August 29, however, had been cloudy all day so that on eclipse day we had to go to camp early to test our final adjustments, go through drills once more and to be sure that all the apparatus worked smoothly. The skies were clear and our hopes for success were high. Outside the roped-off enclosure, the whole town of Daroca was assembled, for it was naturally thought by the people that nowhere could the eclipse be seen so well as where the astronomers were located.

At 11.52 A.M. a little indentation was seen on the western limb of the sun, and the eclipse had begun. The skies were clear with the exception of a cloud here and there, and our most ardent wish was that the clouds would leave the sun clear for the next couple of hours. For the first hour that the moon was creeping over the sun there was nothing of very great moment to notice, but for the next twenty minutes till 1.12, when the sun was blotted out, we were each of us filled with expectancy, for matters began to take on a weird and unnatural appearance. The little blotches of light under the trees, instead of being familiar circles, were

little crescents, exact counterparts of the sun itself. The darkness began to make itself really felt, and without looking at the sun one would know that something out of the ordinary was happening, for the gloom did not in the least resemble that of sunset. A hush fell upon the crowd of assembled and talkative Spaniards when, ten minutes before totality, a big cloud drifted over the sun. Would this cloud move away? Or were we going to be disappointed? It hung there for a space of time that seemed to be an age, while in reality it was only five minutes. It was a big scare, but when that passed, with a shout from us all, there wasn't another cloud anywhere to bother us. Seventeen seconds before the calculated time, with the last disappearing ray of sunlight, the corona broke forth into view. What a magnificent sight it was shining out with its pale, pearly light for a couple of diameters round the edge of the sun, with its streamers and brushes of delicate light! True to prediction, the corona was almost square in shape, and was not at all alike in appearance to the other coronas the writer had seen in 1900 and 1901, with their long fish-tail extensions along the sun's equator and short-curved streamers near the sun's poles. In the upper left-hand quadrant, huge red flames sixty thousand miles high could be seen with the naked eye, and these with a closer view with the telescope resolved themselves into a forest-like structure. Close to the sun the corona was very bright, in fact so brilliant that the eye was not readily able to take in all the details of the faint streamers. As a pictorial effect, without the long equatorial extensions, this corona was much inferior to the two last ones seen. Still it was a magnificent sight, and we were more than thankful for having clear skies for making our observations.

When totality first started we were each and all of us much too busy to take very much notice of our immediate surroundings or even of the corona itself. We could not help becoming aware that our Spanish onlookers outside the ropes were appreciating the show in the skies provided for them without expense. From the noise made each one seemed to be telling his neighbor at the top of his voice just

The Roman Fort (2200 years old) and Moorish Fortifications at Daroca, Spain

Officers and Sailors of the U. S. Navy Assist the Astronomers in Observing the Total Eclipse in Spain

how it happened and what there was worth seeing, and this in spite of the fact that the mayor of Daroca had generously provided half a dozen members of the civil guard to preserve order and keep quiet. For the first half minute the din was so great that it was impossible to hear the seconds counted, or to know exactly when to begin and end the exposures of the photographs. When the Spaniards had quieted down, after their first outburst, all that was heard in the eclipse camp was the steady count of the observer calling out the seconds as they passed, the quiet words of the observers giving commands to their assistants and the click, click of the various pieces of apparatus as exposures were made and plate holders removed. Everything passed off without a hitch, and with the first reappearance of the sun our work was over and we could take a long breath.

We had been favored with clear skies. How many others were equally fortunate? It did not take us long to find out, for the Spanish government had installed right in our camp a telegraph office, and for fifteen days no less than three operators were at our service to send and receive our messages; and for this not a single cent of money was asked or expected. It was found that fifty miles to the west of us, at Alhama, where were the observers from the Lick Observatory under Professor Campbell, there were thin clouds, while one hundred miles to the east along the Mediterranean coast, the Englishmen were even more unfortunate in having the clouds denser. In the northeastern part of Spain at Burgos, more astronomers were located than at any one place, and here too was King Alfonso of Spain. Five minutes before totality it was pouring rain, but as if by a miracle a little blue patch of sky appeared, and the eclipse was seen under perfect conditions. The weather along the eclipse track was: in Labrador, cloudy (no observations made); in Spain, cloudy and clear; in the islands of the Mediterranean, cloudy; on the coast of Africa, slightly cloudy; but further inland and along the rest of the eclipse track the skies were perfect. All three parties of the Naval Observatory were fortunate in having their work unhindered by a single cloud.

My own work was entirely spectroscopic. The photographic plates were developed within the walls of the college of Daroca, and in the long hours necessary for this work I was greatly encouraged and assisted by my good friend the rector of the college, Padre Felix Alvirez. Daily intercourse with this reverend father endeared him to me very much; and Señors Lorente, Soria and Padre Felix made my stay in Daroca one of the most interesting spots of my whole life by the kindness with which they bore my imperfect Spanish, by the interesting bits of history they told of Daroca, and by the deep insight each gave into the courtesy of a Spanish gentleman's heart.

U. S. Naval Observatory Eclipse Station, August 30, 1905
The 40-foot Camera is placed horizontally.

Lick Observatory Eclipse Station, June 8, 1918
The 40-foot Camera is pointed directly at the Sun.

CHAPTER XII

THE AMERICAN ECLIPSE OF 1918

THIRTEEN years after the splendid observing conditions of 1905 in Spain I witnessed my fourth total eclipse of the sun, again as a member of the expedition representing the United States Naval Observatory. On June 8, 1918, the shadow of the moon touched the earth's surface on the Pacific Ocean, far south of Japan. Owing to the revolution of the moon about the earth and to the rotation of the earth on its axis, the shadow crossed the Pacific Ocean at a speed of over a thousand miles per hour. It was well after noon before the shadow reached the American continent, and the eclipse began in the state of Washington. Here the width of the shadow was only sixty miles, so that only those fortunate enough to be within this narrow track were able to see the eclipse in its totality. The eclipse passed southeasterly through Washington, Oregon, Idaho, Wyoming and Colorado in succession. In Colorado, the shadow had dwindled to forty miles in width. After passing through some of the central states, the shadow left the United States at Florida and left the earth's surface in the Atlantic, off the coast of the Bahama Islands.

The eclipse was seen almost exclusively from the United States, and so it will be known as the American Eclipse of 1918. Since more than half the civilized world was in the grip of the tremendous war, it was necessary for American astronomers in the year 1916 and early in 1917 to make their plans to insure that this eclipse should be well observed. Before our own country had become involved in the war, Congress had been asked for, and had made, a special appropriation to defray the expense of equipment and travel for the party from the U. S. Naval Observatory.

In order to help the astronomers of the country to make as intelligent a choice of an eclipse site as possible, the

Naval Observatory, in 1917, had prepared a large scale map of the United States showing among other things, railroad lines, contour lines, and the location of towns, within the eclipse track. The city of Baker in eastern Oregon seemed to be the ideal spot for the government party. The question of clear skies was the all-important one for the proper location of an eclipse party, but fortunately, the U. S. Weather Bureau had a regularly equipped station at Baker, and a record of many years' continuous observations seemed to be the ideal method of securing the desired information regarding the probabilities of good conditions on the day of June 8. As the Weather Bureau promised an absence of clouds and rain with an abundance of clear skies, Baker was chosen with the great hope that it would live up to its good reputation in the matter of weather. The city has about ten thousand inhabitants, is on the main line of the Union Pacific system and is located at an altitude of 3,500 feet above sea level.

In order to set up and adjust the apparatus, five of the party left the East about April 20. These members consisted of Mr. J. C. Hammond, Astronomer of the Naval Observatory, in charge of the expedition, Mr. W. A. Conrad and Mr. C. C. Wylie, assistants at the Naval Observatory, and Dr. L. G. Hoxton and myself of the University of Virginia. After locating ourselves at the Antlers Hotel, we viewed the city in order to find the best site for the eclipse location. Through the kindness of the Chief Engineer of the Union Pacific system, who provided us with excellent photographs and topographic maps, we were not long in deciding upon the Fair Grounds on the edge of the city as the most convenient spot. This was fairly near to the hotel where we lived, the grounds were surrounded by a high board fence which would serve to keep out the idly curious, and the buildings on the grounds were adequate to house our valuable apparatus until put in place. We were in Baker exactly six weeks before eclipse day, and the time was none too long. The apparatus was sent forward by through freight, and though we greatly feared delays, it

arrived safely the second day after our own arrival. To assist in the work of erecting the apparatus, the superintendent of the Naval Observatory had requested the services of five sailors from the U. S. Naval Station at Bremerton, Washington, who were in charge of a chief petty officer. The sailors were carpenters and machinists who assisted the astronomers in splendid style so that ten days before the eclipse, when the balance of the party began to arrive, the apparatus was all erected and partially adjusted, and there remained only the perfecting of the adjustments in order to be ready for the all-important day of the eclipse.

For direct photography of the corona, the largest camera was one of sixty-five feet focal length arranged horizontally, the light from the eclipsed sun being reflected by a coelostat mirror. On eclipse day this instrument was in charge of Conrad. Two smaller cameras, of thirty-six and one hundred and four inches, respectively, were handled by Peters and by Wylie, while two still smaller ones were in the hands of Kempton Adams.

The spectroscopic work of the Naval Observatory party in 1918 called for the use of three concave gratings, each used objectively without slit. The largest instrument was a twenty-one foot Rowland grating of six inches aperture and 15,000 lines per inch. This had a spectrum specially bright in the first order on one side, the grating being kindly loaned by Professor J. S. Ames. Photographic films two by twenty-four inches were used, and it was planned to work from the extreme ultra-violet as far to the red as the length of the films would permit. The second concave grating was of ten feet radius and 15,000 lines per inch, the grating belonging to the Naval Observatory. This was used in the first order and gave the same dispersion as the instrument employed in Daroca, Spain, in 1905. By the use of special emulsions kindly prepared by Dr. C. E. K. Mees of the Eastman Kodak Company, an attempt was made to photograph farther to the red end than in 1905. The third one was a very short focus grating of two meters radius and of six inches aperture belonging to the Astrophysical Observatory of the Smithsonian Institution. This grating gave very

brilliant spectra but with little dispersion. Dr. P. W. Merrill of the U. S. Bureau of Standards had had great experience in photographing the infra-red by the use of dicyanin, and to him was assigned the task of securing the spectra at the end of great wave-lengths by means of plates stained with this dye. In addition to Dr. Merrill, I had the following capable assistants in looking after the spectroscopic program: Miss Bigelow and Miss Hopkins of Smith College and Dr. Hoxton of the University of Virginia. All three spectrographs were arranged horizontally and the light was fed into them by means of coelostats.

The adjustment and accurate focusing of the spectroscopes was a long and tedious process demanding at all times infinite patience and splendid mechanical skill. The exquisite focus shown by the developed spectra taken at Baker in 1918 was largely due to the capable assistance given me by my colleague of the University of Virginia.

Fortunately for the work of preparation, and true to the prediction of the U. S. Weather Bureau, no rain fell during the entire stay of the astronomical party in Baker. According to the " oldest inhabitant," the season was unusually dry even for eastern Oregon. By some mysterious force unknown to the astronomers, the eclipse seemed to exert some potent influence over the weather. At any rate, it was asserted by many of the rural papers that no rain could be expected until the eclipse was over. But if an absence of rain was experienced there was no lack of clouds, nor were the clear skies we had been led to expect afforded us. As the time for the eclipse drew nearer, the continued appearance of clouds began to cause anxiety among us. Would they interfere with the eclipse, and at the last moment make all the weeks of careful preparation of no account? If this had indeed happened, it would not have been the first event of the kind. Unfortunately for the astronomer, his work is always at the mercy of the clouds and the weather. But to have the whole work fail through clouds at the time of the few precious minutes of the total eclipse, — that is indeed the keenest sort of disappointment! Some astronomers seem to be always unlucky and always experience cloudy

THE AMERICAN ECLIPSE OF JUNE 8, 1918
Corona photographed with the 40-foot camera of the Lick Observatory.

weather on their eclipse expeditions, while on the other hand others are always lucky, and sometimes after all hope is abandoned, a rift will appear in the clouds and the eclipse at totality be seen in all its glory. Would we at Baker be lucky or unlucky, would the clouds interfere or not? Nearly all the days spent in Baker, according to the classification of the U. S. Weather Bureau, were actually clear. A " clear " day is not necessarily cloudless from morning till night, but rather one when the " sky averages three-tenths or less obscured, from sunrise to sunset." Clouds, however, gathered almost every day shortly after noon, and this condition was usually accompanied by very high winds that at times rose to the strength of a mild gale. The eclipse was to occur during the middle of the afternoon, and at this time of day the skies were generally overcast. These same conditions prevailed over the whole of the western United States along the path where the astronomers were located. It was well to be an optimist under such conditions of sky, for the pessimist became more and more wretched as the day of the eclipse drew near and his law of averages showed him the almost certain chance of thinly clouded sky during the total eclipse.

Fortunately, so far in my eclipse experiences I had been among the lucky astronomers. In 1900, at my first eclipse, the weather was ideal, — not a single cloud in the whole sky. In 1901, I was a member of a rather large party which traveled half way round the world, of which only four of a total of thirteen saw the eclipse, the other nine witnessing the eclipse eclipsed by clouds. I was one of the fortunate four. Again, in 1905, there were many clouds which spoiled the researches of many parties. At Daroca, in Spain, a few minutes before totality a dense cloud covered the sun, but it cleared away before the all-important time and the total phase was seen through a brilliantly clear sky. Three lucky chances out of three made a fine average. The hope was that June 8 would make it four out of four!

By May 30, the whole party had assembled in Baker. A full week was given up to the final adjustments, and to the drills that were to play such an essential part in the work

on eclipse day. During the partial phases of the eclipse, very few observations of importance were to be made; all observations of value came during the period of totality which lasted for one hundred and twelve brief seconds. If a slide of a plate holder should stick in place so that it could not be removed, or a lens were not uncapped at the proper time so as to let in the light, the whole work of an instrument might come to naught. On each day of the week preceding June 8, drills were gone through several times, in the morning and again in the afternoon. These drills were so well carried out that on eclipse day each and every one performed excellently the task allotted to him with the result that everything passed off without a single hitch.

As the days in June progressed towards the eighth, there was an air of excitement as each astronomer grew more keyed up to the task before him. Would Saturday be clear? But more especially, would the two minutes from 4:04 to 4:06 P.M. be clear? The skies were anxiously watched during the last days, but alas! almost every day at eclipse hour they were overcast. The optimist reasoned that if it were cloudy all the days before June 8, then on eclipse day perfect weather would surely be forthcoming; while the pessimist on the other hand argued that so many cloudy days meant still one more of the same character, so there would be no use trying to do anything.

Saturday, June 8, dawned with the sky overcast with thin, filmy clouds. The sun was well visible through these clouds, however, and it was possible to examine again the focus that had been obtained with the spectroscopes and with a touch here and a touch there to decide that everything was in perfect condition. During the morning the drills were again practised, and these seemed to promise success. The weather during the six weeks had not held up the work, and everything that thought and work could do seemed now to have been accomplished. The astronomers who had been on the ground for the whole six weeks of preparation had the pleasant consciousness that all of their allotted tasks had been completed, that every little detail had been thought of and that perfect success would certainly crown their efforts if only the clouds would clear away. But during the course of the morning, the clouds grew thicker instead of thinner, and it did indeed seem as if there was little chance of a clear sky.

The first contact was to take place at 2:36 P.M. Shortly after noon, the city of Baker took upon itself the aspect of a holiday. Though the day was Saturday, all stores were closed from three until five in the afternoon so that everyone should have a chance to see the phenomenon. Naturally everyone in Baker wished to go to the eclipse site at the Fair Grounds, to watch the astronomers at work. At the eclipse in Spain, this had been permitted with the result that the whole town had assembled, each inhabitant jostling his neighbor to get as close as possible, and each apparently talking at the top of his lungs, with the result that such a din arose when the eclipse became total that it was impossible to hear the seconds counted off to give warning to the astronomers when to change their plate holders.

In order that this might not happen again, the residents of Baker were told that the gates of the Fair Grounds would be closed, and that absolutely no one would be admitted within the enclosure, and the mayor of the city sent a guard of Boy Scouts to see that these orders were obeyed. Most of the townspeople repaired to the hills to the southeast of the city from which there could be obtained a fine view of the valley and the Elkhorn range, and they were directed to look especially for the shadow of the moon which would come across the landscape at the speed of thirty miles a minute or 1800 miles per hour.

No appreciable improvement in the skies was observed from noon to the time of first contact. Through a thin patch in the clouds, Mr. Hammond, using the five-inch visual telescope, observed the beginning of the eclipse and made a record of it. The clouds if anything became thicker after this so that at three o'clock it was impossible to see even where the sun was. Little thin rifts appeared at times, so that it was possible to see the moon encroaching on the face of the sun. At three thirty, a patch of brilliantly blue sky was seen off to the north-

west and as the precious minutes dragged along it became evident that the clouds were moving in such a way that it was quite possible that the blue patch would reach the sun in time for totality. Fifteen minutes before the total phase the clouds were so dense that had totality occured then, the scientific results would have been nothing; but the blue sky was coming nearer and it might arrive in time.

Without looking at the sky, one realized that something unusual was happening. The light of the sun became so feeble that even the birds felt the unnatural aspect of things and sang their songs as if they were going to rest. The cocks in the nearby farm crowed. The wind, which was ordinarily blowing at this hour, was quiet. All nature was hushed. Even the seasoned astronomers who had seen two or three eclipses before felt the thrill of the unusual spectacle. And still the question was, would the clouds clear away in time!

At five minutes before totality the warning signal was given by Chief Petty Officer Welsch of the U. S. Navy who was to watch the chronometer and count the seconds. This signal summoned each man to his post. One last look was given to the apparatus to see that everything was in place, the plate holders were adjusted, — and then we waited. "Two minutes" before was called out, and then "one minute," still again "thirty seconds" before the expected time of totality. The clouds by this time had thinned considerably, the patch of blue sky was only a short distance away. The plan had been that after the signal of "thirty seconds," there should be nothing said until the word "Go" told that the total eclipse had begun. I was to watch for this with a pair of binoculars, before one glass of which a direct vision spectroscope had been arranged. This was the plan followed in Spain with complete success. But due to the thin clouds at the beginning, it was impossible to see the spectrum lines with the spectroscope, and the signal "Go" was actually given by Mr. Hammond who was using the five-inch telescope. No sounds disturbed the work of the party except the call of the seconds as the time passed and the brief words of command and shift of plate holders as

AMERICAN ECLIPSE OF 1918

Lick Observatory photograph with 40-foot Camera showing "Eagle" and other prominences.

each member of the party did his allotted task. Ten seconds after totality commenced, the clouds, thin at the beginning, had still further thinned, and at mid-totality the conditions were even further improved. What a gorgeous spectacle then met the eye! The sun was now in a very thin wisp of cloud with blue sky on either side. Although the cloud would undoubtedly detract from the scientific results, still it greatly enhanced the pictorial effect. The corona could be seen stretching for a short distance from the sun's edge, but most remarkable of all were three great tongues of flame, one immediately at the top of the sun, one on the lefthand edge, and still a larger one on the right edge of the sun. These shone with a brilliant scarlet light, and made the eclipse of 1918 memorable as the eclipse of color. As the end of totality approached the thin clouds became still thinner, — and two minutes after the eclipse was over the sun had reached the blue patch of sky. If the eclipse had occurred only two minutes later, or if the party had been only half a mile to the northwest, the sky conditions would have been perfect! If, as I have already said, the eclipse had taken place fifteen minutes earlier, the scientific results would have been nothing at all. The optimists had won out.

We had indeed been fortunate. But farther west at Goldendale, Washington, where the Lick-Crocker party was located, a change of weather had happened which amounted almost to a miracle. The account by Professor Campbell runs as follows: "The total phase of the eclipse occurred at 2:57, local mean time. By great good luck a small rift in the clouds formed mostly at the right place and right time. The clouds uncovered the sun and its immediate surroundings less than a minute before totality became complete, and the clouds again covered the sun less than one minute after the total phase had passed. The small clear area was very blue and the atmosphere was tranquil."[1]

The developed photographs exhibit the painstaking care of the astronomers in procuring the precise focus, with the result that all of the photographs show exquisite definition. The thin clouds did not interfere at all with the details of

[1] *Lick Observatory Bulletin*, *10*, 2, 1918.

the prominences or flames surrounding the sun. Those taken with the sixty-five foot camera exhibit the prominences in splendid detail on a scale where the sun is more than seven inches in diameter. The longer exposures for procuring the extensions of the corona were not quite so successful, since the thin, fleecy clouds cut down the fainter streams of coronal light. The smaller cameras showed the same results as the larger ones, — splendid detail in the inner corona, but the corona not of very great extent. All the photographs unite in showing many polar rays, and they also exhibit some plumed arches of great beauty. The corona was of the sun-spot maximum type, but with more polar streamers than were expected.

The spectroscopes procured photographs of exquisite definition, but these photographs suffered much from the clouds which cut down the amount of exposure that at best is none too great.

What was perhaps the most interesting piece of scientific work accomplished at the 1918 eclipse owes its conception to Mr. Edward D. Adams, of New York, who has shown his great interest in science by the founding of the Ernest Kempton Adams fellowship which is awarded each year by Columbia University for researches in the domain of pure science. Upon becoming a member of the United States Naval Observatory party, Mr. Adams took upon himself the responsibility of trying, by some method, by photography, by a drawing, or by a painting, to procure a reproduction which would show the beauties of the corona, and which should be true not only as to form but more especially as to color. Unfortunately for science, it is impossible to obtain a satisfactory representation of the corona and the sun's surroundings by photography. The corona is very brilliant near the edge of the sun, but the intensity fades very rapidly. The eye can take cognizance of the details in spite of the great changes in brilliance, but not so the photographic plate. To obtain the faint extensions of the corona which are readily visible to the naked eye, a comparatively long exposure is necessary. This long exposure causes so much overexposure in the brighter inner regions of the corona that

all detail there is lost by being burnt out. Short exposures give us the inner corona in exquisite detail, but the outer corona is then lost through shortness of exposure. Many attempts have been made to cut down the relative exposure by means of mechanical devices — but none of these have been entirely successful. Heretofore, the only success in representing the corona has been obtained by taking photographs with different times of exposure and with different cameras in order to procure photographs with detail both in the inner and brighter parts of the corona, and in the fainter outlying portions. After the eclipse is over, a composite drawing is usually made from the examination of different photographs. This method has given several satisfactory drawings, but they still have left much to be desired. However perfect they may have been as drawings, they took no note of color. Mr. Adams took upon himself the task of finding the right man to draw and paint the corona. Color photography could not help out in procuring the right color, and there was left only the possibility of finding an artist who would have the true scientific spirit, and who could combine an accurate sense of form with a refined perception of color. Mr. Adams was successful in finding Mr. Howard Russell Butler, a portrait painter of note, who has developed a shorthand method of noting both form and color.

During the eclipse, Mr. Butler sat on a lofty perch overlooking the eclipse instruments, and from which he could obtain a fine view of the sun. The task he had taken to himself was no small one. And moreover this was the first corona he had ever seen!

The methods followed by Mr. Butler in painting the corona have been described by him in *Natural History*, *19*, 244–271, 1919, and reprinted as Vol. II, part 6, of the *Publications of the Leander McCormick Observatory*. An abbreviated summary of his description is herewith given:

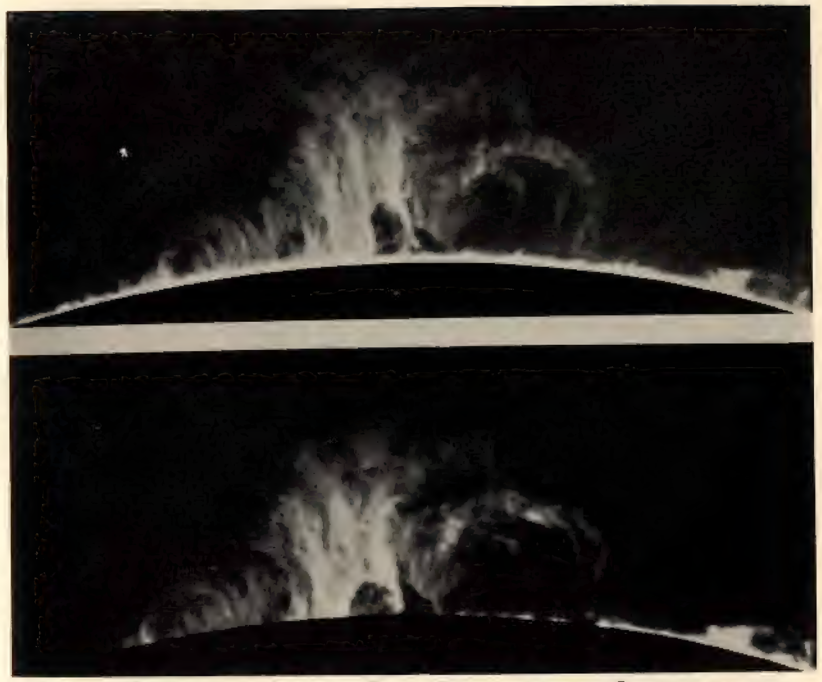
" As a portrait painter I have usually asked for ten or twelve sittings of two hours each: now I was asked to render my subject in 112 seconds. The method of procedure therefore became all-important.

"All reports of the so-called 'inner corona' agree that the part nearest to the sun is very brilliant and this inner corona is usually described as whitish in color. The transition from this inner portion to the far less brilliant outer part is quite abrupt.

"As regards the prominences, — while often discernible with the naked eye, it is necessary to have a good glass to get the details of shape and to study the color rightly. The Naval Observatory put at my disposal a fine pair of Zeiss binoculars, which proved of the greatest value. I realized in advance that my hardest task would be to portray these prominences in their proper color and brilliancy. According to Professor Mitchell, I was to expect them to have a color not unlike that of the hydrogen line $H\alpha$ in the spectrum, possibly slightly modified by the much fainter bluish line; and ample opportunity to study these lines in the spectroscope was given to me. How best to render this color in paint and to give it its luminous character was the problem. Realizing that this would necessarily be the brightest tone in the picture and that it would have to stand out brilliantly against the tone of the inner corona, also bright, I set to work to produce the brightest possible red; that is, the one which stood highest in a scale of values of which varnished ivory black was zero and the best lead white (commercially known as silver white) was 100. I tried French pastels and water colors, the latter over Whatman paper, but ultimately found that I could do best with oil paint.

"The process of obtaining this red decided upon for the final picture, but which takes more time than I had at Baker, was to prepare a hard surface of silver white, well dried, to paint over that a thin coating of zinc white tinged with orange cadmium, and, when that was perfectly dry, to glaze it richly with rose madder or garance rose doré. This gave the tone with its fiery quality, but alas, its value, while the highest that I could get, was down to 65 or 70 in the black and white scale. The highest value obtained by mixing wet colors at Baker was about 60.

"Granting this to be the highest note that I could have in my picture, I next addressed myself to the lowest. Would



Calcium Spectroheliograms of Solar Prominences on October 10, 1910

These photographs secured by Slocum with the Yerkes refractor show great changes taking place in ten minutes of time.

this be the sky or the dark surface of the moon? Regarding the color and value of the clear sky during solar eclipses, there were varying opinions. Many drawings show the moon as black against a sky represented by a medium gray. These I believed to be incorrect and found them so. The moon, having a less luminous quality than the sky and surrounded by the brilliancy of the corona, should appear slightly darker by optical illusion. The sky value was at any rate the safer note to work from and, except for the slight variation alluded to in the moon, it would surely be the darkest value in the picture.

"Assuming then a sky value of say 25 and a prominence red value of say 60, the total variation in values would thus be limited to 35 points, — surely a small range with which to reproduce so brilliant a phenomenon.

"The method of working finally adopted may be called a shorthand method. It was to have a sheet of white cardboard on the easel with a series of concentric circles and radii drawn upon it in advance. One of these circles was to have the same diameter as the photographs of the moon to be taken in the sixty-five-foot camera, namely, seven and three-eighths inches. There was to be an inner circle of half this diameter and outer circles whose diameters were respectively one and one half, two, and two and one half times that of the inner circle. I expected to use the seven and three-eighths inch diameter, and did actually use it, but I was thus prepared, in case of an unexpectedly extended corona, to reduce the scale to one half and get everything on the cardboard. In front and beneath my cardboard was a finished sample picture of a corona, painted in advance as I *expected* it would appear, and my plan was to indicate by initials at points on my cardboard the variations of color from this picture; thus *b* was to mean a variation toward blue from the sample picture, and *y* more toward yellow. I wrote out the procedure as follows and tacked it alongside the easel. Practice enabled me to allot a certain number of seconds to each item.

Procedure	*Seconds*
Note value and color of sky	10
Draw value line on moon	10
Note colors of moon	10
Draw outline of corona	20
Use Zeiss binoculars	20
Record positions of prominences	10
Note color and value of prominences	10
Note colors and values of corona, etc	20
	110

"Then my plan was to paint a first picture from this resulting memorandum, while the impression was vivid, and as soon as there was sufficient light to proceed by.

"The observation station was in the Fair Grounds at Baker, about a mile and a half from the center of the town. It was surrounded by a wall and low buildings, which insured privacy. A grand stand ran north and south with a double door opening from the top aisle. This door, intended as an exit or fire escape, opened upon a platform with flights of steps descending both ways. This platform was assigned to me and on it I erected a strong easel and shelves extending to right and left and making an angle with each other. Wind guards and braces were added. The platform faced west and, as the sun at the time of the eclipse was to be about 12° south of west, the position could not have been better. It had also a great advantage in being so high up that I could look over the surrounding walls and low buildings and get a fine view of the valley and of the Elkhorn Range in the direction of northwest along the line of the approaching shadow. By keeping the north half of the door into the grand stand closed and boring a small hole through the door, an excellent camera obscura was obtained, the image of the sun appearing on a tilted white covered board on the inner side of the door. I had been advised and had determined not to look at the sun for a considerable time before totality, so as to avoid what is known as retina-fatigue, which is certain to result from looking at the brilliant crescent. The camera obscura gave all the information wanted as to the diminishing crescent and yet left me free to watch for the approaching shadow.

"Standing with the sun back over my left shoulder — it was at an elevation of about 45° — I looked at the diminishing crescent on the face of the camera obscura until the call 'one minute' was heard. Then, turning my eyes to the northwest, I gazed at the north end of the Elkhorn Range and the intervening valley. Roosters were crowing loudly on the neighboring farm; a greenish pallor overspread the landscape, — but it was not very dark. To the northwest, however, the sky was growing dark. The last half minute seemed long. My eyes were fixed on the sky line. Suddenly the entire range fell to a deep low-valued blue, and simultaneously the lower part of the sky above the range turned to a rich yellow, inclining to orange, streaked with two horizontal blue-gray clouds. Above me the sky darkened rapidly. For an instant the valley retained its light green color and then the shadow seemed to rush toward us and all was engulfed as the call 'Go' was shouted. The accompanying color illustration of the approaching moon shadow is from a 'memory' painting made the next day, the time ten seconds before totality.

"Turning on my heel, I looked at the corona, blazing steadily in the heavens as if it had always been there. The clear space in the sky had not quite reached the sun. The thin intervening cloud extended to right and left of the sun and stood out with its edges illuminated and sharply defined against a velvety night sky of wonderful bluish violet.

"Here was a new problem. I had not expected the cloud. I began by drawing the outline of the cloud (slightly nearer the sun than it actually was so as to get both cloud and sky well on the cardboard), then entered the value and color of the sky as 30 *bv*, and the cloud edges which were higher and silvery. The cloud itself, of varying thicknesses, was warmer in tone than the sky and played, I estimated, between 30 and 40. The moon was about the same value and much grayer than the sky. I was not conscious of any considerable variations of value in the moon and failed to put in the value line. The blackishness of the moon and the center lighter than the edges were undoubtedly optical illusions. Next a quick outline of the corona was made, most

attention being paid to the larger rays. Then the binoculars (which had been previously adjusted and focused) were used. Two splendid prominences, slightly pinker and lighter than I had expected, appeared — one near the top of the sun and the other on the left side below the horizontal. I gave these the highest value which I then thought could be produced by mixing oil paints, *viz.*, 60 *r*. A rose-colored glow stretched along the lower right side of the limb, the value of which was first recorded on the chart as 50.

"I recorded two lines of values for the outer corona. I saw no distinct separation of the inner and outer coronas. On the upper left extension greenish and yellowish tones were recorded. No time was wasted on tones thought to be correct in the sample picture. On the whole, the corona was less blue than my sample and it retained brilliancy farther out than I expected. Had it been seen against the blue sky it probably would have extended still farther and its disappearance might have been more gradual. Two sections of the so-called inner corona were very brilliant, although of course not as high in value as the prominences. These were next to the limb and were very neutral as to color. I outlined them and marked them 'whitish,' but got one of them in the wrong place. This brought my eyes to the picture for several seconds. About the ninety-fifth second I looked up and was surprised to see that the pink glow had lengthened out and risen in value. This change was due to the motion of the moon, which had by that time uncovered a magnificent solar eruption, but I had no time to take up the glasses. I outlined this glow, its value fully up to 60, which I entered afterward.

"Toward the end I re-outlined the corona, indicating rapidly the polar rays, for the accurate drawing of which, as well as for that of the prominences, I intended to rely on the photographs. These rays were decidedly apparent. Suddenly I was blinded by the first of the 'Baily's Beads,' or the first glimpse of the solar crescent broken by the rough limb of the moon. It looked like a miniature sun radiating in all directions. And all was over!

"Thanks to the privacy of the grounds and the considera-

THE APPROACHING SHADOW OF THE MOON,
BAKER, OREGON, JUNE 8, 1918.
Note the unnatural color of the landscape.

tion shown me, I was able to proceed at once with my first oil sketch, and for two hours worked uninterruptedly. The next day, June 9, I painted the picture of the approaching moon shadow over the Elkhorn Range as I remembered it and also a second oil of the corona.

"While disappointed in not seeing the corona in a cloudless sky, the thin veil had its advantage from the artist's standpoint. It added mystery and the effect was picturesque. The brilliant corona burned through the thin veil as if it were not there. Probably only the outside edges of the corona were affected.

"On the tenth, the photograph negatives were shown to me. Those of the sixty-five-foot camera were seven and three-eighths inches in diameter, the others considerably smaller. I now saw, in minute detail, the two prominences which I had recorded and the mighty cyclone which had been increasingly revealed as the eclipse neared its end, because of the direction of the moon's motion. There were many other minor prominences.

"I now made careful drawings of these prominences from the negatives and of the variations in shading of the surrounding corona. Many arches were found springing over the prominences, and a few rifts or dark channels radiating from the limb but never coming very close to it. The negatives showed very clearly the hairy polar rays, not always radial in direction, and the beginning of a wing springing from the upper right-hand limb of the sun.

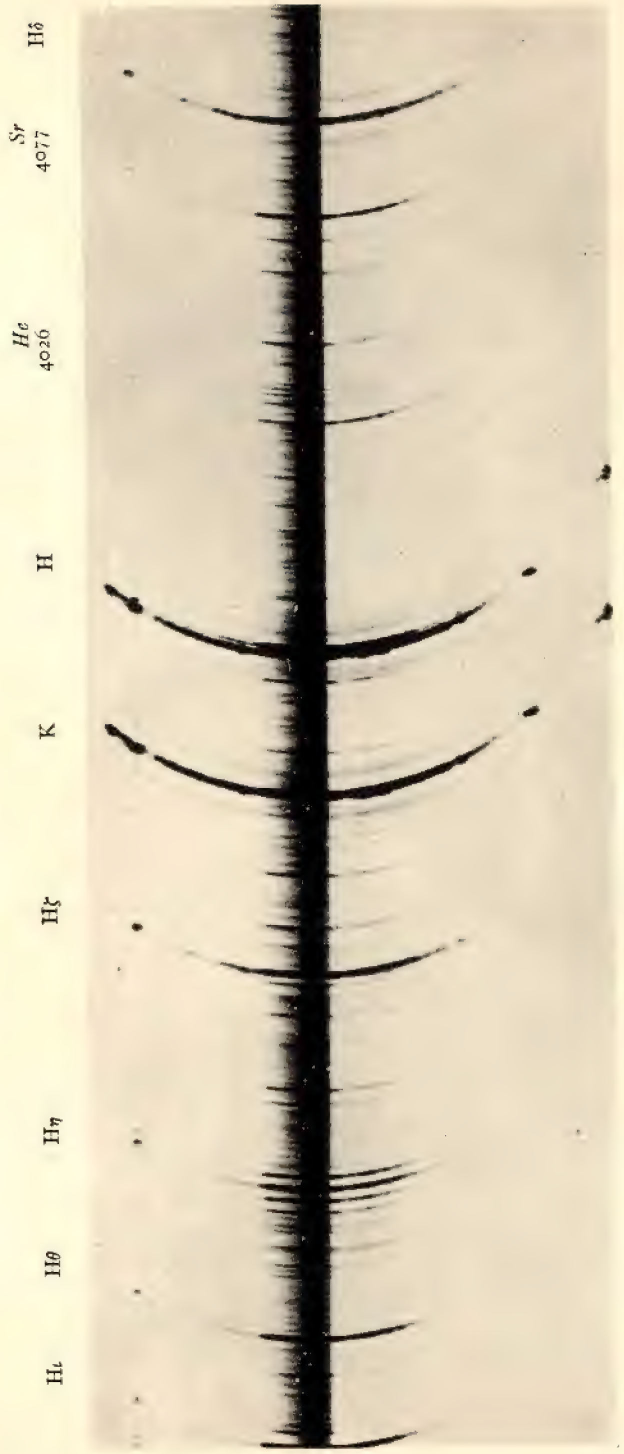
"By careful process painting, as already described, I have been able to force up the value of the prominence reds to 67. I also concluded to reduce the value of the clear sky from 30 to 25, thus obtaining a range of 42 points instead of 30, an increase in the ratio of 7 to 5. In this new scale the other values take their proportional places.

"Three paintings were made, the first immediately after the eclipse, the second on the succeeding day and the third after all data had been secured. This final painting is the one reproduced in the frontispiece."

One of Mr. Butler's paintings has been presented to the American Museum of Natural History in New York by Mr.

Edward D. Adams. This canvas is mounted in the Astronomical Room which is kept darkened but with the corona painting illuminated by indirect lighting. Those who have been privileged to see this painting have pronounced it a thing of rare beauty. The astronomers who saw the 1918 eclipse and who have seen the picture look upon it as a marvel of perfection, true both as to form and color, a great work of art which has the added advantage of being scientifically accurate.

The world of science owes a great debt of gratitude to Mr. Butler for his exquisite corona, but even a still greater debt tq Mr. Adams, through whose conception, generosity and enthusiasm the painting of the corona became possible.



THE FLASH SPECTRUM AT THE TOTAL ECLIPSE OF AUGUST 30, 1905

Photographed by a concave grating without a slit. Reproduced as a *negative* enlarged sixfold from the original. H and K are the strongest lines in the flash spectrum and the vapor (Ca+) extends to an elevation of 14,000 km. above the sun's surface. The calcium line H is seen separated from the hydrogen line Hε.

CHAPTER XIII

THE FLASH SPECTRUM

HALF a century of remarkable progress in solar physics since Young discovered the flash spectrum does not witness any decided unanimity of opinion regarding the exact location of the solar envelope wherein lies the absorption causing the Fraunhofer lines. On the one hand appears Young's original view that the reversing layer is a thin shell but a few hundred miles in thickness, while on the other extreme we have Lockyer's opinion that such a reversing layer does not exist and that the corona is merely the cooler and rarer portion of the chromosphere. Although observations taken at the time of an eclipse must be relied upon for the chief information by means of which this question can be settled, still there are many other lines of investigation that contribute their results towards the same problem.

The flash spectrum may be observed visually or photographically, with or without a slit, and by means of prisms or gratings. Photographs of the flash spectrum taken with a slit have some advantages over those taken without slit. Since the lines in a spectrum are but images of the slit itself, it is obvious that, under the temporary conditions of eclipse observing, it should be easier to obtain a sharp focus with a slit spectrograph than with a slitless instrument. In securing photographs of the flash spectrum when a slit is used, it might be placed radial or tangential to the sun's surface. If placed in the radial position, the fact that the reversing layer is very shallow would permit a very narrow spectrum only, and it is conceivably possible that a mountain on the moon which might happen to be projected on the slit might cover up most of the image of the reversing layer. With a tangential slit,

it is difficult and well-nigh impossible during the few excited moments of a total eclipse to be certain that the image of the sun formed by the projecting lens is always precisely tangent to the slit. Even if this were possible, the resulting spectra could give no information whether the section photographed was close to or far from the surface of the photosphere. Present-day researches regarding the flash spectrum demand large dispersion. The work of the U. S. Naval Observatory party in 1900 showed conclusively the difficulty, or one can now say, the impossibility, of securing large scale photographs of the whole flash spectrum with a slit, and it is safe to say that no similar attempts will be made in the future.

For obtaining these large-scale spectra, either a prism (or prisms) or a grating may be employed. Each has its advantage and each its disadvantage. The great advantage of the prism is the greater light-gathering power, the light being concentrated in one spectrum, but on the other hand the grating possesses many points in its favor. The lines in the prismatic spectrum are crowded together at the red end and widened out at the blue part of the spectrum, thus entailing much difficulty in the determination of wave-lengths. The grating gives a normal spectrum, permits of higher dispersion, and gives higher resolving power, a larger extent of spectrum and probably better definition. Gratings either plane or concave may be used, but with a flat grating a lens becomes necessary to bring the spectrum to a focus, and such a lens introduces aberrations and absorption of light, and consequent loss of definition. Up to the present the best results on the flash spectrum at an eclipse have been obtained by means of a concave grating without slit. The arrangement of the apparatus is of the greatest simplicity. The light from the sun falls directly on the grating where it is diffracted and brought to a focus on the photographic plate. If the grating and the photographic plate are each perpendicular to the radius of the grating, then the spectrum is normal, or to speak in more exact terms, the spectrum departs very little from a uniform scale of wave-lengths.

Used in the ordinary Rowland form of mounting in the laboratory, one of the well recognized advantages of the concave grating is the property of "astigmatism," whereby the spectrum lines are increased in length. If the astigmatism should be of approximately the same amount when the concave grating is used without slit, then as a result of lengthening out the chromospheric lines, which are necessarily curved, the definition would be ruined. Consequently, in making plans for 1900, when concave gratings were used for the first time at an eclipse, the Naval Observatory party did not dare attempt to use such a grating without slit. The successful photographs of stellar spectra[1] secured by concave grating used objectively showed however that these fears were groundless. Moreover, Runge's discussion of the theory of the concave grating, in Kayser's *Handbuch der Spectroscopie, 1,* 450, 1900, proved that the amount of astigmatism for a concave grating used in the objective form would be so minute that it could have no harmful effects on the definition of the spectra.

It might not be out of place to call attention to the very great difficulty always experienced by eclipse observers in securing sharp focus with their spectroscopes; in fact one very prominent feature of eclipse spectra in the past has been the continued succession of photographs poorly focused. One method of securing focus frequently made use of has been to apply the final adjustments by utilizing the spectrum of the disappearing crescent of the sun a few minutes before totality. During the excitement and nerve-racking tension of these moments, a perfect adjustment can be obtained in this manner only as the result of a happy accident, — and this method should never be resorted to under any circumstances. For instruments of small dispersion, the light from a star may be utilized for securing focus, if happily some bright star is conveniently located, but for spectrographs of the greatest dispersion the spectra even from the brightest of the stars are too weak. For large instruments, there is accordingly left only the possibility of securing focus on the sun itself several days

[1] *Astrophysical Journal, 10,* 29, 1900.

before the eclipse by the employment of some sort of collimating device which will give a parallel beam of light coming from a slit source. For the use of the U. S. Naval Observatory party at the eclipse of 1905, Jewell constructed a collimator consisting of a slit at the common focus of two concave mirrors, lenses not being used because of their chromatic aberrations. Several methods of placing the slit at the common focus of the mirrors will at once suggest themselves to any ingenious eclipse observer, one of the simplest being to bring the image of a distant hill on the slit plate, shifting each mirror until this is accomplished.

The concave grating used at Daroca, Spain, in 1905 was of ten feet radius, it was ruled with 14,438 lines to the inch and was of four inches aperture. The grating was kindly loaned by Professor F. A. Saunders. The distance between grating and photographic plate was five feet, and since the spectrum was brought to a focus on a circle of radius thirty inches, it was necessary to usé celluloid films instead of glass plates. Grating and photographic plate holder were enclosed in a light-tight box of seasoned mahogany. A coelostat was used to reflect the sun's light horizontally to the grating. Unfortunately, any coelostat mirror may become warped from its plane surface by the heat of the sun, and herein lies another difficulty to be surmounted in securing spectra of perfect definition. At the eclipse of 1901, Barnard had a camera sixty-one feet in focal length. This focal length determined from observations of stars differed by more than six inches from the focus derived from the sun, the difference representing the effect of temperature on the shape of the mirror. The alteration in the focal length of a mirror with change of temperature is well known to every astronomer who uses a reflecting telescope. The grating spectroscope must be very firmly mounted on solid piers of masonry or heavy timbers in order that the tremors of the apparatus caused by the wind or by the changing of the plate holders may quickly subside. It is manifestly difficult to mount such an instrument of large dispersion on an equatorial mounting or on a polar axis, with the grating in consequence directly exposed to the sun's rays.

This method would indeed get rid of the coelostat mirror with its possible change in figure, but if this plan were followed, it would probably be a case of "from the frying pan into the fire." In 1918, the films used with the ten-foot grating were $1\frac{1}{4}$ x 14 inches coated by a special emulsion to give as uniform an extent of spectrum and as far into the red as possible. The emulsion was kindly prepared by Dr. C. E. K. Mees of the Eastman Kodak Co. Six films were placed parallel in a single plate holder, and with a little practice it was possible to shift quickly and quietly from one film to the next.

It is impossible to exaggerate the importance of securing the photographs of the flash spectrum at the proper instants of time so as to secure the spectra of the layers of the chromosphere as close to the photosphere as possible. At an eclipse, there are two manifestations of the flash, one at the beginning and one at the end of totality. Before the beginning of the total eclipse, the Fraunhofer lines persist as long as there is any portion of the photosphere visible, but when the moon entirely covers the sun's surface, or at the very instant of the beginning of totality, there is the sudden reversal of the Fraunhofer spectrum to that of bright lines. If one watches the phenomenon visually with some form of spectroscope, he will see many of the high level lines reversed many minutes before totality, particularly at the cusps. There are two methods of securing the photographs at the proper times. One is that followed by the Lick Observatory expeditions of using a moving plate with the spectrum narrowed in width by an auxiliary slit placed close to the plate. One objection to this scheme is that the portion of the spectrum that goes through this slit might perchance not be a representative section due to a mountain on the moon being projected on the slit, or to the presence there of strong continuous spectrum. Another and much more serious objection to such a plan is that such spectra can give no information whatever concerning the heights to which the various solar envelopes extend above the photosphere. Another variation of the same method is obtained by the use of a cinema or movie camera, and with a prism for forming

the spectra. Such an arrangement was employed in 1918 by Frost in Wyoming. The disadvantage of this method is that it is impossible to use other than the regular commercial movie films and their size is so small that it is possible to bring under investigation only a very limited portion of the spectrum.

The plan for securing photographs at the proper times followed by the Naval Observatory parties since 1900 is an old familiar one. A pair of binoculars is used. Over the right half a direct vision spectroscope is employed. Jewell constructed the Naval Observatory instruments and utilized a plane grating and plane mirror for the direct vision spectroscope. As it was possible to employ any particular portion of the spectrum one wished, that section extending from blue to green was brought into the field of view. With a pair of binoculars and such an attachment, it was possible with the left eye to watch the disappearing crescent of the sun, shielding the eye, if necessary, by smoked glass, while with the right eye the emission lines could be watched as they appeared one after the other with the approach of second contact. Armed with this, the first flash can be observed and the exposure started with great nicety. For the second flash the exposure should begin at least five or more seconds before the calculated end of totality, and should terminate with the first trace of the reappearing sun. A delay of one-tenth of a second in ending the exposure may readily bring ruin to this exposure. In photographing the flash spectrum at an eclipse it is evident that the important photographs are two, one at the beginning and one at the end of totality. Ordinarily, additional photographs are made, just before and immediately after totality, for the Fraunhofer and any emission lines. During totality, several short exposures are given, just after the first flash and again before the second flash, for the vapors of greater elevation, with a long exposure at mid-totality to obtain the spectrum of the corona which appears as a series of complete rings. Such photographs of the coronal spectrum, however, do not permit of wave-length determinations of the highest precision for these can be accomplished only by the use of a slit spectrograph. It need hardly be added that the times of first and second flash, recorded preferably on the chronograph, will furnish excellent observations of the times of beginning and ending of the total phase of the eclipse.

If the flash spectrum were an *exact* reversal of the Fraunhofer lines, both as regards wave-lengths and intensities, the eclipse observations could add but little to our knowledge of solar physics. In such a case, the precious moments of a total eclipse should be devoted to the investigation of other lines of research. In fact, the flash spectrum is interesting and important only in so far as it differs from spectra taken under ordinary conditions. Eclipse spectra can furnish information regarding: (1), heights above the photosphere of the layer of gases forming each line of the spectrum; (2), intensities of the spectral lines; and (3), wave-lengths.

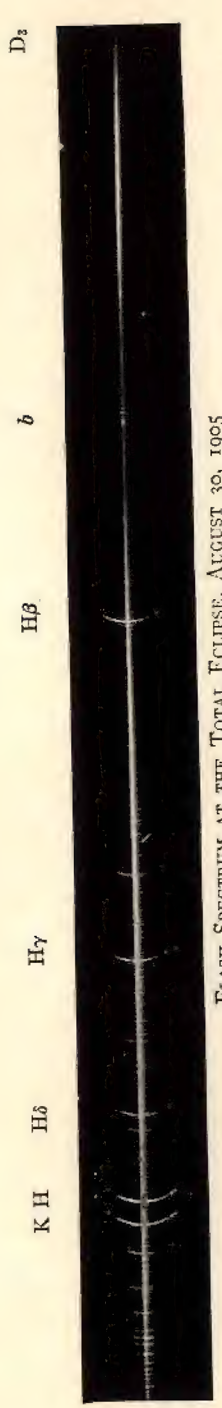
In view of the many recent researches on the sun, a knowledge of the *thickness* of the layers of gases forming the chromosphere is of the utmost importance and vital to the solution of solar problems. These heights can be measured directly in no other manner than by means of flash spectra taken without slit, the length of the cusp given by each line furnishing the elevations of the various vapors. It is probable that at the present time these heights furnish the most important addition to solar knowledge that can be given by flash spectra.

The *intensity* of a spectrum line depends both on the width and on the blackness of the photographic image of the line. It is unfortunate that in all spectra, whether of dark or bright lines, whether determined in the laboratory or in the observatory, it is ordinarily impossible to have a scale for the designation of relative intensities which is other than arbitrary. With such a scale the strongest line in any spectrum may be represented by 10, by 100, or even by 1000, while the weakest line receives the number 1, or 0, 00, 000, or even 0000 as in the case of Rowland's atlas. Such scales being arbitrary are seldom uniform, and it is consequently very difficult to compare the values of the intensities of one spectrum assigned by one observer with

those investigated by another. It will be shown later that the flash intensities differ in marked degree from those of the ordinary solar spectrum. Recent researches help to explain the causes of these radical differences.

The measurements of the *wave-lengths* of eclipse spectra taken without slit present a problem of peculiar difficulty. Ordinarily in these spectra, the intensity of the line is greatest close to the sun's surface and tapers off gradually as higher elevations are reached. With the stronger lines, there is a spreading of the photographic image by irradiation, an effect well known to all spectroscopists. Apparently, therefore, to secure a consistent set of wave-lengths it is necessary to set the line of the measuring engine tangent to the moon's limb, or rather at the position the moon's edge *would have taken,* if there had been no photographic spreading. Such measurements require judgment that can come only as the result of experience. Accurate wave-lengths from eclipse spectra are, after all, of secondary importance, for they are valuable only in so far as they afford a ready means of positive identification of the sources of the lines from a comparison with Rowland's and other wave-lengths secured with much greater dispersion.

The distinguishing features of the photographs of the flash spectrum taken in Spain in 1905 are: (1), the good definition; (2), the normal spectrum; (3), the low levels photographed; and (4), the large extent of spectrum. In addition to the spectra obtained by the concave grating, spectra were also secured by a plane grating. The spectrum was measured from 3300 A to D_3 for concave grating, and to 6200 A for plane grating. The flash spectrum from the concave grating is shown on page 220. In order to reproduce it on nearly the original scale much of the ultraviolet is omitted. This illustration is reproduced as a positive where the spectral lines are *bright*. For a more ready comparison with Rowland, the enlargements are negatives. It will be noticed at once from the original and from the enlargements, that the continuous spectrum at the middle of the arcs was quite strong. Running down the center of this band of spectrum there is a small strip where the con-



Flash Spectrum at the Total Eclipse, August 30, 1905

Photographed with a concave grating without slit. Region from 3700 A in the violet (to left) to 5900 A in the orange (to right). Reproduced as a *positive* (bright lines on a dark background), nine-tenths original size. Being taken without slit, the lines are not straight but curved. Each spectral line is an image in a different color (or different wave-length) of the heated vapors forming the sun's atmosphere called the chromosphere. The *lengths* of the separate arcs give the only means yet available for measuring the *heights* that the vapors extend above the surface of the sun.

tinuous spectrum is not so intense. This may be best seen in the green and orange regions. On the enlargements, particularly at the violet end, may be seen several parallel strips of continuous spectrum, one of considerable strength running through a prominence near the top of the spectrum and several fainter strips through prominences below the center. Interesting differences will be noted by comparing the shapes of the various lines. The stronger lines, like H and K and the hydrogen series, show many protuberances. Chief among these may be mentioned a large prominence at the top of the photograph. H and K show a large prominence in violent motion and which also was at such a high level that it is shown by none of the other lines.

On the original photographs most of the strong lines show a fine reversal at their centers.

The spectrum obtained by means of the concave grating extends from 3318 A to D_3, a distance of 9.5 inches (23.5 cm). From H to D_3 the distance is almost exactly 7 inches (17.78 cm). The dispersion is 1 mm = 10.8 angstroms, about equal to the three-prism dispersion near $H\gamma$, of the Mills spectrograph of the Lick Observatory or the Bruce spectrograph of the Yerkes Observatory. The dispersion with the flat grating is a trifle greater, and amounts to 9.1 angstroms per millimeter.

The spectra being taken without slit, the lines instead of being straight are crescents, each crescent being a monochromatic image of the chromosphere. As stated above, erroneous values of wave-lengths would be obtained if the micrometer wire, when measuring, was made to bisect each line of the spectrum. What success was obtained in this attempt at measurement may be seen by comparing the wave-lengths of the chromosphere with Rowland's values. For all lines of the chromospheric spectrum taken with concave grating, having an intensity less than 25 on the assumed scale, the difference from Rowland averages but 0.02 angstroms, which corresponds to an error of measurement of 0.002 mm. For lines with intensities greater than 25, there are, for the reasons just specified, greater differences. Usually for the intense lines, the chromospheric wave-length

is too great. The reason for this is assumed to be simply an error in judgment in setting the measuring wire, not enough allowance having been made for the spreading of the heavy lines of the spectrum.

At second flash, where the best photograph was secured, the chromospheric light shone through a low-lying plain on the moon's edge. This plain had a sharp termination at one end and a gradual elevation toward the other. The result of this was that the short chromospheric arcs are sharply terminated at one end and gradually dwindle off toward the other. (The meaning of this will be more evident by reference to the photographs.) Advantage of this was taken in carrying out the measurements. This sharp termination of the arcs occurred exactly in their middle, as may be seen by looking at the longer arcs. At this sharp edge, the arcs were exactly perpendicular to the length of the spectrum, and consequently all measures for wave-lengths were made by setting the micrometer wire at this sharp termination of the arcs. Unfortunately, for the measurer, the continuous spectrum was rather strong throughout the spectrum and it became necessary to use a strong illumination. (I felt great hesitancy about using any chemicals to reduce the continuous spectrum, and I desired to measure the original spectra rather than copies.)

Theoretically the spectra of the chromosphere, from both plane and concave gratings, are normal. Practically, they are not quite normal for the reason that the end of the plate-holder would have cut off some of the incident light if adjusted to give the normal spectrum. The difference in scale at the two ends of the spectrum amounted to about one-half of one per cent. Consequently, for first approximations to wave-lengths, a constant scale-value was assumed; and setting up this value on a multiplying machine, wave-lengths were obtained with the greatest ease.

During the measurement, it was found that the celluloid film of the spectrum was very sensitive to changes in temperature, the result being that it became necessary to reduce separately the wave-lengths measured at each sitting.

After obtaining approximate wave-lengths, it was necessary to reduce them to some consistent standard. It was felt that at the present status of the system of wave-lengths it was most advantageous to use Rowland's values. Consequently, comparisons were made with each and every well determined line in the chromosphere which correspond to a *single* line, *not a blend*, in Rowland's Tables. These comparisons for a limited region of measures made at one sitting gave differences which were nearly constant.

The next step in the determination of wave-lengths was an accurate adjustment to Rowland's values. This was done by the well known method of Professor Carl Runge of the University of Göttingen, who, while these reductions were being carried on, was Kaiser Wilhelm exchange-professor at Columbia University. As each region measured at one time was a comparatively small portion of the spectrum, the method consisted essentially in plotting the differences *Mitchell* − *Rowland* and passing a straight line through them. Instead of plotting their differences, the method adopted was to use least squares to determine two constants corresponding to the intercept on the *Y*-axis and the slope of the tangent. Ordinarily from twenty to forty lines in Rowland could be used as standards. Generally at each sitting a few lines measured at the preceding sitting were remeasured.

Thus piece by piece the measures were reduced to Rowland's scale. Since wave-lengths from the measures at each sitting were reduced separately, the final wave-lengths are the means of the three or four separate measurements. Also, since each measurement was carried on absolutely independently of all others, with the spectra set at different readings of the scale, it is felt that the systematic differences from Rowland, if existing at all, are exceedingly small.

The differences in wave-lengths between chromosphere and Rowland may be the results of several causes: first, fundamental differences depending on the distribution of the vapor in the chromosphere. As stated above, there are believed to be no such fundamental differences of wave-length of appreciable size other than those caused by errors in judgment in knowing where to set the micrometer wire

for the more intense lines. The second cause for the difference *Mitchell – Rowland* results from the uncertainty in knowing what wave-length to assume for Rowland for the blended lines. As will be shown later, there are enormous differences in intensities between the Fraunhofer spectrum and the chromospheric spectrum. Manifestly, on account of these differences in intensity, wrong values of wave-lengths would be obtained, either by taking an average of the wave-lengths of the different lines blended, or by weighting them according to their intensities. But what wave-lengths are to be assumed for blended lines? This dilemma is well known to all investigators of stellar spectra. The only logical way for securing a consistent scale of wave-lengths was to adopt a rule and stick to it rigidly, and not try to manufacture a wave-length for each blended line considered in Rowland. This rule was the one used by most spectroscopists, viz., to combine wave-lengths by weighting the lines according to their intensities in Rowland. If necessary to combine with a line 0 on Rowland's scale, the intensity of this line was taken as 1 and one unit was added to each of the intensities of the other lines. The third cause of discrepancy between Mitchell and Rowland was, of course, errors of measurement, both in Mitchell and in Rowland.

The most characteristic difference between the chromospheric and the Fraunhofer spectra is found in the relative intensities of the lines. The system of intensities adopted for the chromospheric spectrum is purely an arbitrary one, in which 100 represents the strongest lines like K and Hγ, and 0 that of the weakest line. Naturally the intensities depend on the character of the photographic plate used, but partial allowance was made for the decrease in sensitiveness of the plate in the green and yellow regions. In estimating intensities, one is unconsciously influenced by the breadth of the lines, so that the values for intensity give a somewhat combined appraisal of the blackness and breadth of a certain line. These at best are but estimates, but they are perhaps comparable in accuracy with estimates of intensities by others.

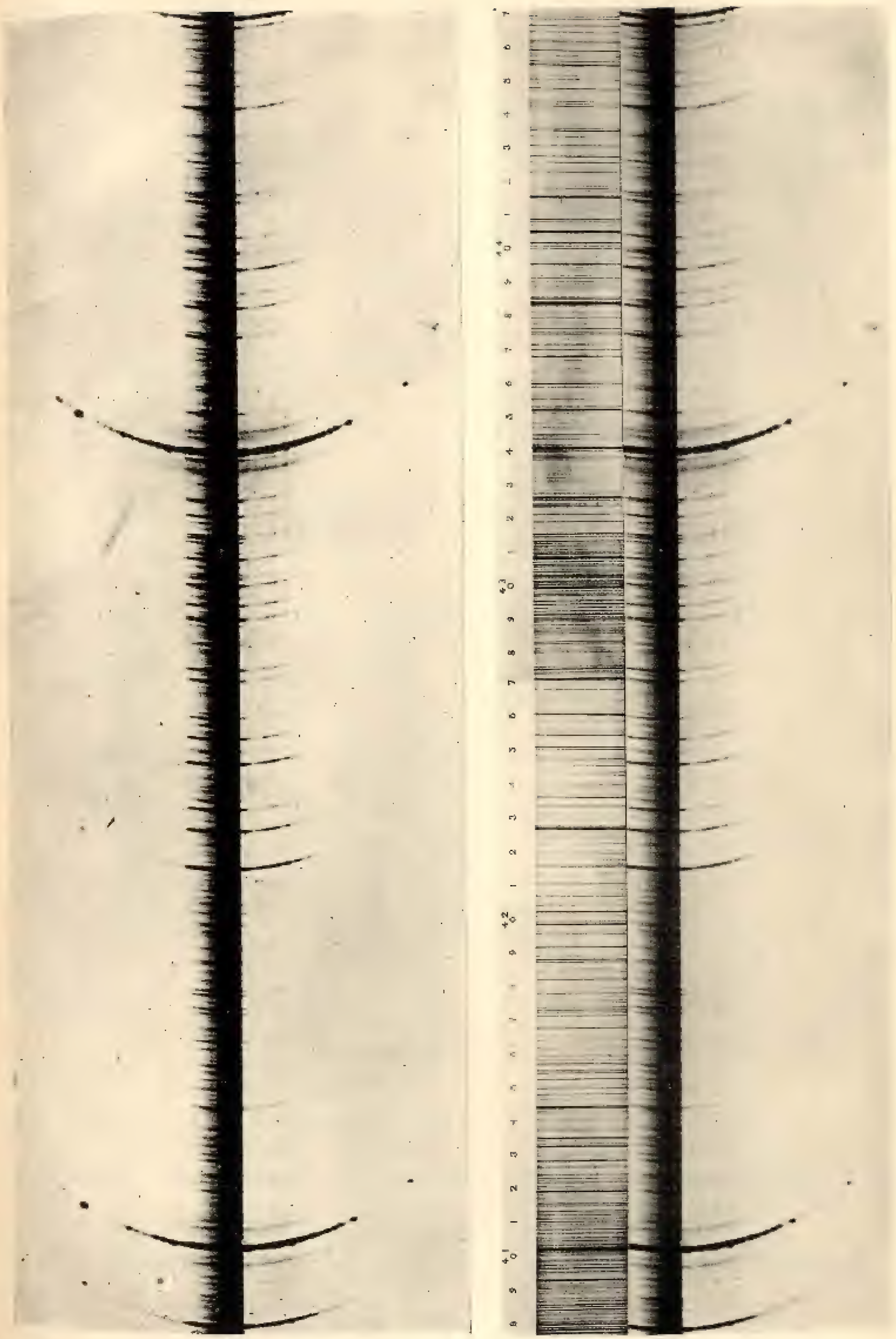
The reasons for the characteristic differences in intensities between the dark line Fraunhofer spectrum and the chromospheric spectrum will be evident on a moment's reflection. Consider a Fraunhofer line coming from the center of the sun's surface, and assume that the absorption is caused by a reversing layer 500 miles in thickness. The light coming perpendicularly from the photosphere can be absorbed by the atoms in this 500-mile layer. At the time of an eclipse, the light of the chromosphere comes *tangentially* from the sun's surface, and not perpendicularly, with the result that the chromospheric light is affected by a depth of 20,000 miles of atoms. (The line of sight from a layer 500 miles in thickness passes through 20,000 miles of solar atmosphere when tagent to the sun's surface.) This has an important bearing on Saha's theory, as will be explained in Chapter XVII.

Moreover, let us consider two different elements in the sun's envelope; one of these elements is low in density and extends high in miles above the sun's photosphere; the other element is heavier and its molecules are contained in a shallower layer about the sun. It is easy to imagine that the absorption caused by the molecules in the two layers of gases under consideration might be the same where the light passes radially through the gases, for instance, coming from the sun's center. Under these circumstances, it is probable that the two gases would give lines of equal intensity in the Fraunhofer spectrum. At the time of an eclipse, however, the exposure is a progressive one. The moon gradually passes before the sun, with the result that the exposure on the low-lying vapor is relatively very short compared with the other assumed vapor of greater elevation. Hence, it is readily seen that although the two gases may give lines of equal intensity in their absorption spectra, they will not necessarily do so in their emission spectra; the low-lying heavy vapor will give in the chromosphere short arcs, while the other assumed vapor will give longer arcs of greater relative intensity. Though there are other contributing causes, the main factor for the differences in intensity between the dark- and bright-line spectra of the sun is the

heights to which the vapors extend. H and K and the hydrogen lines are the strongest in the chromosphere mainly for the reason that calcium and hydrogen extend to greater elevations than any of the other elements.

As a matter of fact, there are such enormous differences in the intensities of the Fraunhofer and flash spectra that placed side by side, as they are on page 226, the spectra seem to belong to stars of two different types rather than to the same object under different conditions. It is these differences that make observations of eclipse spectra of the greatest value in widening our knowledge of solar physics. The chief differences in intensity for the stronger lines are found in the elements helium and hydrogen. As is well known, no helium absorption lines are ordinarily found in the sun, whereas in the eclipse spectrum the helium lines are conspicuous by their great strength. In the Fraunhofer spectrum there are only four hydrogen lines visible, while in the flash spectrum there is the whole Balmer series, no less than thirty-four lines being measured in the 1905 plates.

Perhaps one of the most striking differences between the intensities of lines in the two spectra (which at the same time will illustrate the difficulty experienced in finding the wave-lengths of blended lines), will be seen by referring to a line in the chromosphere measured at 3709.50 A. In Rowland's tables there is a line at 3709.389 A, belonging to *Fe* with an intensity 8. With eclipse spectra of less accuracy than those of 1905, one would naturally identify the chromospheric line at 3709.50 as a *Fe*-line, especially since this *Fe*-line has an intensity in Rowland of 8. For this photograph of the flash spectrum, however, the discrepancy in wave-lengths is too great. The next line in Rowland's tables is an unidentified line at 3709.540 with an intensity of oN. Reference to Exner and Haschek's tables shows that the latter line is due both to *Zr* and *V*. In the arc, the lines of both elements are absent; in the spark the intensity for *Zr* is 15, for *V* is 3. Although this line does not appear in Lockyer's list of enhanced lines, or when the lines are stronger in the spark spectrum than in the arc, the intensities from Exner and Haschek show that both *Zr* and *V* are



a b c

SPECTRUM OF THE CHROMOSPHERE, AUGUST 30, 1905

Region from *Sr* 4077 to *He* 4471. In *a* and *c* is found the same region of the flash spectrum taken without slit, enlarged six-fold from the original, in *b* is a section of Rowland's *Atlas*, reduced fivefold with attached scale of wave-lengths. Great differences in relative intensities are found in the two spectra *b* and *c*.

enhanced. Consequently, it is seen that the chromospheric line at 3709.50 more nearly corresponds to the weak line at 3709.540 than to the much stronger *Fe*-line at 3709.389. But what wave-length is to be assumed for the blended value of these two lines from Rowland? Manifestly an entirely erroneous value will be obtained if, according to the rule adopted (and given above), the *Fe*-line is given a weight of 9, the other of 1.

In identifying the sources of the lines in the chromospheric spectrum the greatest possible care was exercised. Naturally the first step was to make a detailed comparison with Rowland's Table of Solar Spectrum Wave-Lengths, where is found a catalogue of about 20,000 lines of which number nearly 6,000 were identified by Rowland. In the quarter of a century since these tables were published, marvelous progress has been made in all branches of spectroscopic work. Rowland compared the solar spectrum with the arc spectrum of various metallic elements. By photographing solar and metallic spectra side by side on the same plate by the well-known Rowland method, it was possible to identify the source with certainty on account of the great dispersion employed. The work of many investigators has shown that the character of the lines of a spectrum are intimately connected with the conditions surrounding the electric arc. Lockyer's "long and short line" method is an evidence of this, and moreover various pole-effects, Stark-effects, etc., show that not only the intensities but the wave-lengths of arc lines may be altered by different observing conditions. As an example, we might cite the case of the magnesium lines at wave-lengths 3938.5, 3986.9, 4057.6 and 4167.4 A. In the arc under ordinary conditions, these lines are broad and unsymmetrical, and their measured positions show no well determined correspondence with the solar lines. If, however, the arc is put into a vacuum, the broad lines are changed to sharp ones, and the coincidences with solar lines are at once apparent. Hence many lines in the solar spectrum have been identified both by changing the conditions of the arc and by carrying out innumerable observations in various parts of the spectrum with a greater and greater degree of accuracy.

Considerable progress has also been made in the identification of solar lines by following Lockyer's lead and investigating spectra under the conditions of the spark as well as under those of the electric arc. Further identifications have followed from the detailed study of band spectra. The first band in the solar spectrum, discovered in 1874 by Lockyer, has its head at 3883 A and is generally ascribed to cyanogen. According to Runge this band is due to nitrogen, but the cyanogen origin seems to be the more probable one. A host of fine lines, particularly in the green, have been identified by Rowland to be due to carbon. More recently Newall proved that the G-group in the Fraunhofer spectrum was due to hydrocarbons, and Fowler found ammonia and water-vapor bands in the ultra-violet.

The task of identifying the sources of spectrum lines is one of the greatest difficulty, and numerous have been the mistakes made by various investigators. Too much care, therefore, cannot possibly be exercised. To make the identification of the lines in the flash spectrum more complete and to give information regarding the relative strength in arc and spark spectra, it became necessary to look up practically every table of metallic spectra that had ever been published. Of greatest value were Exner and Haschek's tables, and also those appearing in Kayser's *Handbuch der Spectroscopie* and in the *Astrophysical Journal.*

The method adopted was to take out from the above sources all lines of all metallic spectra which would have wave-lengths approximately close to the chromospheric line under investigation, setting down on paper at the same time the intensities in both arc and spark. This work naturally consumed a great amount of time. After having tabulated the intensities of arc and spark from all available sources, it was necessary to choose from these the one or more arc and spark lines which appeared to agree with the lines of the chromosphere. This was a comparatively simple matter on account of the accuracy of wave-lengths of lines of the chromosphere, experience telling which of the possible identifications was the probable one.

In this part of the work many differences were found

from the identification given in Rowland's tables, differences expected from the fact that the chromospheric spectrum is not necessarily the same as the ordinary solar spectrum, and also from the fact that in the quarter-century since Rowland's work was completed, much has been learned concerning the spectra of the metals. Where Rowland has given identifications, they were in most cases found correct.

This close comparison with the spectra of the elements made the identification of lines rather certain. But Rowland's tables were made from spectra having a dispersion of approximately ten times the dispersion of the chromospheric spectrum (21-foot radius in the second order compared with 5-foot focus in first order, the gratings having nearly the same number of lines per inch). Naturally, lines which appear single in the chromospheric spectrum may be a blend of two or more lines with the greater dispersion. But lines which appear as a close pair or a blend in the chromosphere must be the result of the blend of corresponding lines in Rowland. On account of the great differences in intensity of the chromospheric and Rowland spectra, it was difficult to be always sure of identifications until photographs were compared side by side. The original photograph of the flash spectrum was enlarged six times. Rowland's great Atlas was reduced five times. Since the flash spectrum was nearly normal, it was possible to procure both spectra on a close approximation to scale. On page 226 are portions of the two spectra printed side by side. This comparison of spectra will perhaps speak more strongly, than any words or comparison of wave-lengths, concerning the sharpness of the original spectrum of the chromosphere. On account of the small variations from the normal spectrum (noted above) it was impossible to obtain an exact match in scale in the two photographs. Those who are interested sufficiently will be able to carry the comparison along line for line.

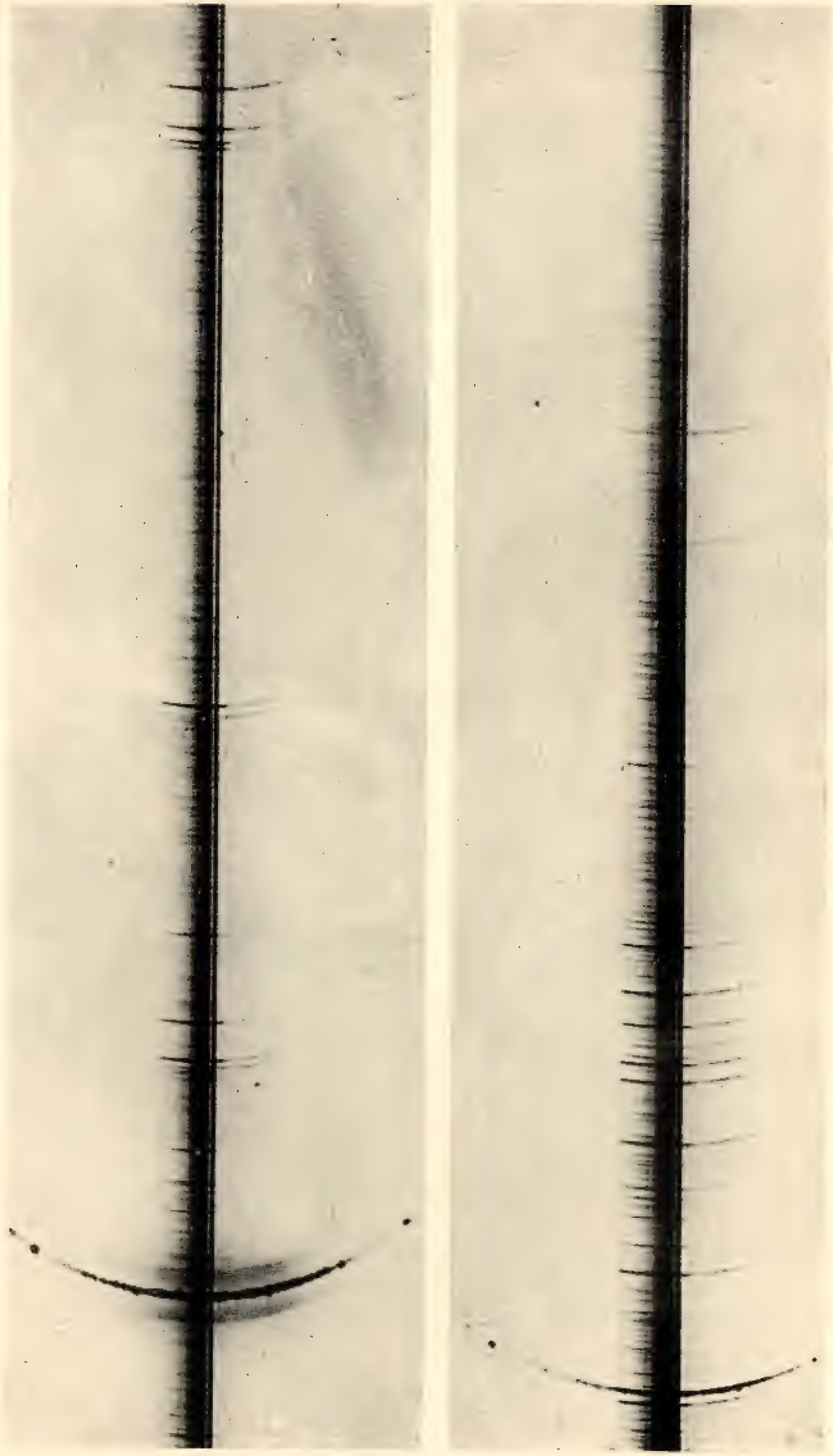
These photographs of chromospheric and solar spectra side by side, were of the very greatest service in decisions on the relative importance of elements forming the lines of the flash spectrum. Perhaps of the greatest value was the informa-

tion gained concerning the appearance of the lines in Rowland under the identical dispersion as obtained in the chromospheric spectrum, and from this it was possible to decide rather positively what lines in Rowland become blended together under the smaller dispersion.

As already stated, these slitless spectra give a ready means of determining the heights to which the vapors forming the chromosphere extend above the photosphere by measurement of the length of the chromospheric arcs. For the values herewith given, the sun's semi-diameter was assumed to be 15′50.″7, the augmented semi-diameter of the moon, 16′35.″7. From these semi-diameters were calculated the heights corresponding to various half-lengths of arcs, and a table was constructed (which it is not necessary to print). A protractor was made on glass with a radius equal to that of the chromospheric arcs on the enlarged spectra above referred to. To obtain the length of the arcs, it was necessary only to lay the glass protractor on an enlarged print of the chromosphere and read off degrees from the protractor. The small table gave the corresponding height in kilometers.

The sharp termination of the chromospheric arcs referred to on p. 222 is very near to the middle of the longer arcs. It was assumed that this termination was at the middle of the arcs, and the half-lengths of the shorter arcs were accordingly measured. In the case of the longer arcs, their whole lengths were measured.

Attention should be called to the fact that the heights of the chromosphere determined in this manner, by the measurement of the angular length of the cusps, can afford no great accuracy in the determination of the *absolute* heights in kilometers to which the various layers extend above the photosphere. The method depends on the visibility of the ends of the cusps. It is quite possible, and probable, that vapors extend in detectable amounts to elevations beyond the limits visible in the cusps. The heights derived by this method can therefore only represent a mean height and cannot be expected to furnish the maximum



SPECTRUM OF THE CHROMOSPHERE, AUGUST 30, 1905

Regions from Hγ (below) to *b*-group in green (above). *4686 (He+)* and *4713 (He)* are visible in the lower section.

heights to which the vapors in detectable amounts extend. Attention should likewise be called to the fact that the heights measured in this manner cannot give the elevations above the photosphere, but rather above the average level of the layer photographed in this particular flash spectrum. With these limitations, the method is capable of furnishing the relative heights of the layers producing the individual spectrum lines with a fair degree of accuracy.

The detailed account of the measurement of the flash spectrum of 1905 has been published in *Astrophysical Journal, 38,* 407, 1913, and in the *Publications of the Leander McCormick Observatory,* Vol. II, part 2. Much of the above discussion was taken from this publication. Altogether 2841 lines were tabulated. In some portions of the spectrum, on account of the great density of the continuous spectrum already alluded to, it was difficult to set the measuring line on these faint lines. If it had not been for the continuous spectrum, it is certain that many hundreds of additional spectral lines could have been measured. As a matter of fact, no lines were included in the 2841 enumerated in the tables unless they were measured in two or more separate measurements. Even many lines measured at least twice were not included, for it seemed unwise to increase the length of the tables, by including lines which could not be more or less positively identified by comparison with Rowland. In attempting to measure the faintest lines, it was at once realized that it was easy to draw on one's imagination and fancy that a line existed where there was possibly nothing more than an accidental lining-up of silver grains, in spite of the fact that a rather low power of about 5 was employed in the measurement. It is believed that very few lines are included in the 2841 which have not a real existence in the chromospheric spectrum, in fact only 126 lines are included which have not been identified with lines in Rowland.

The sensitivity of the plate diminished rapidly beyond wave-length 5700 towards the red. Between wave-lengths 3318 and 5700, there were 2734 lines measured, or an aver-

age of 115 for each hundred angstroms. The region of maximum sensitivity of the plate was between wave-lengths 3800 and 4500, and in this portion 1012 lines were measured, or 145 lines per hundred angstroms, which corresponds to 15.6 lines for each millimeter.

CHAPTER XIV

HEIGHTS OF VAPORS IN THE SOLAR ATMOSPHERE

THE depths of the various layers of gases surrounding the sun have an importance which is very vital in all theories of solar physics. Eclipse spectra furnish the only means yet known of directly measuring these depths. Comparisons of the flash spectrum with the solar spectrum taken under ordinary conditions reveal many important conclusions, the first of which is that wave-lengths are identical in the flash and in the Fraunhofer spectrum. This statement can be true only within the limits of accuracy attainable in the measurements of wave-lengths of the flash spectrum, or expressed in other terms, it may be said that no differences between the two spectra exceed 0.02 angstroms. The flash spectrum must therefore be regarded as a true reversal of the ordinary spectrum of the sun since every strong line in the solar spectrum, without any exception, is changed to a bright line at the beginning and at the ending of totality.

Although the wave-lengths in the two spectra are identical, this is far from being true with the relative intensities of the lines. In the flash, many lines appear which are not found in the ordinary solar spectrum; furthermore, some strong lines in the Fraunhofer spectrum appear as weak lines in the flash, and *vice versa,* weak lines in the sun are strengthened in the spectrum of the chromosphere. Differences in intensity signify differences in electrical, thermal and pressure conditions of the vapors producing the lines, and consequently an intimate study of such dissimilarities will give valuable information regarding the solar atmosphere.

According to the identifications of Rowland (Young, *General Astronomy,* p. 215) the elements in the Fraunhofer

spectrum arranged in the order of the *total* number of identified lines in the spectrum are for the first twenty-five elements as follows: *Fe*[1], *Ni*[2], *Ti*[3], *Mn*[4], *Cr*[5], *Co*[6], *C*[7], *V*[8], *Zr*[9], *Ce*[10], *Ca*[11], *Sc*[12], *Nd*[13], *La*[14], *Y*[15], *Nb*[16], *Mo*[17], *Pd*[18], *Mg*[19], *Na*[20], *Si*[21], *H*[22], *Sr*[23], *Ba*[24], *Al*[25]. In the chromosphere, on the other hand, the order is very different: *Fe*[1], *Ti*[2], *Cr*[3], *V*[4], *C*[5], *Ni*[6], *Zr*[7], *Co*[8], *Mn*[9], *Ce*[10], *Sc*[11], *Nd*[12], *Y*[13], *La*[14], *Ca*[15], *H*[16], *Gd*[17], *Sa*[18], *Er*[19], *He*[20], *Sr*[21], *Ba*[22], *Mg*[23], *Si*[24], *Eu*[25].

By comparing the relative orders of the elements in these two lists for sun and chromosphere, and also having regard to the general intensities of the lines in the various elements, we find that the elements can be divided into three groups as follows:

GROUP I. — *Lines strong in the sun, strong in the chromosphere:*

Ca, Mg, Al.

GROUP II. — *Lines relatively stronger in the chromospheric than in the solar spectrum:*

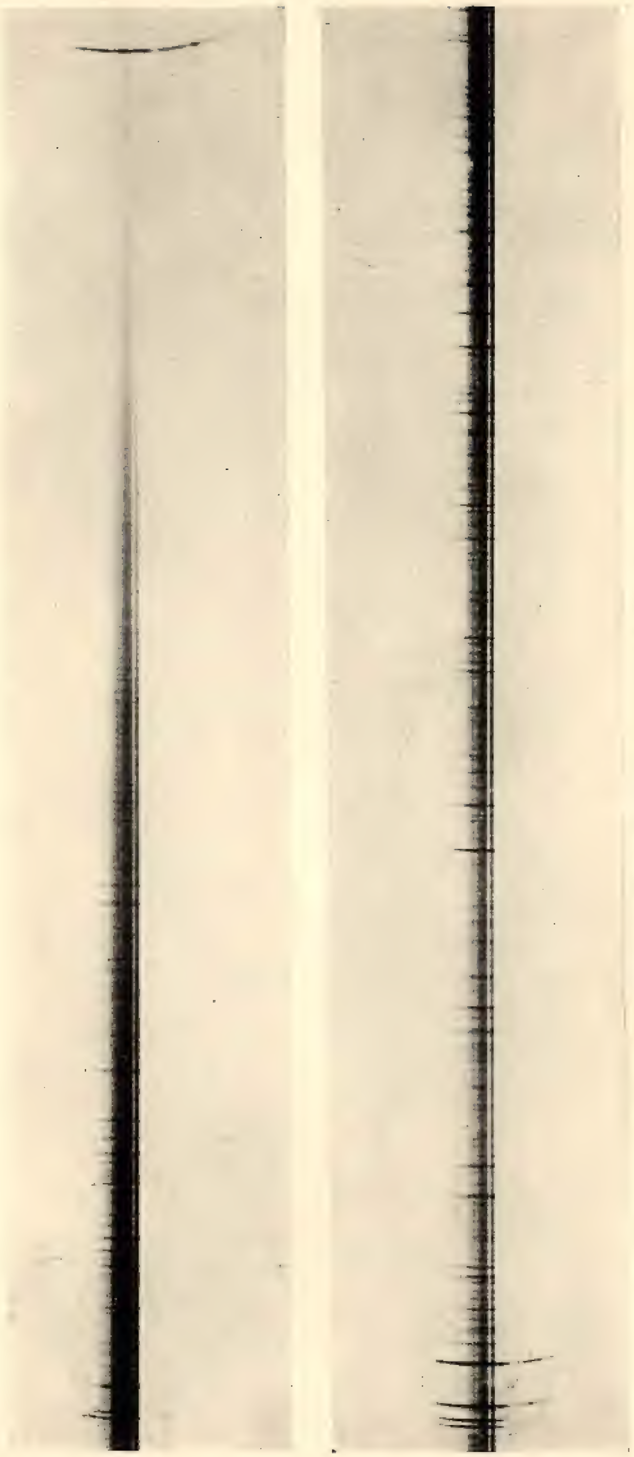
H, He, Ti, Cr, C, V, Zr, Sc, La, Y, Sr, Ba, Nd.

GROUP III. — *Lines relatively stronger in the solar than in the chromospheric spectrum:*

Fe, Ni, Co, Mn, Na, Nb, Mo, Pd.

Although *Fe* heads the list in sun and chromosphere, it is put in the third group along with *Ni* and *Co*.

In the flash spectrum the elements arranged according to the intensity of the *strongest* lines give the following sequence: *Ca, H, He, Ti, Mg, Sr, Sc, Cr, Ba, Fe, Al* and *Y*. This order differs materially from a similar table for the Fraunhofer spectrum given in Young. In the lists of total number of lines, *Fe* stands first in each case. *Ni* and *Co* are second and sixth in the solar spectrum, but become sixth and eighth, respectively, in the flash spectrum. *V* is the eighth element in the Fraunhofer spectrum but fourth in the chromosphere. *Nb, Mo,* and *Pd* appear in the first list but not at all in the second, while in the chromosphere is found *He* which is absent in the ordinary spectrum. The



SPECTRUM OF THE CHROMOSPHERE, AUGUST 30, 1905
Regions from *b*-group (below and to left) to helium D_3 (above and to right)

rare earths *Gd, Er* and *Eu* are represented relatively by more lines in the flash than in the ordinary spectrum.

Interesting results are obtained when the total number of lines identified in the flash spectrum are arranged according to the periodic tables of the elements. This is given in the table on page 236.

For each element in the table there is given: in the first line the atomic *number* and the chemical symbol, in the second line is found the atomic *weight,* and in the third line in *italics* the total number of lines in the chromosphere. The mark (?) is found with the elements *Nb, Mo, Ag* and *Cd* to signify that there are no strong lines in the chromosphere resulting from these elements, but they may possibly be represented by weak lines in combination with stronger lines of other elements. Ten of the rare earths are represented in the flash spectrum by a total of 233 lines, *Ce, Nd* and *La* being responsible for 67, 54 and 43 lines, respectively.

Ca of atomic weight 40 is apparently an unusual element, with remarkable properties, since it is represented by the very strongest lines not only in the sun and chromosphere, but also in the arc and spark as well. The solar lines H and K due to *Ca* are much stronger than those of the very light elements *H* and *He.* This fact, taken in connection with the important rôle that *Ca* plays in stellar spectra, signifies that this element has an exceptional importance in the periodic table. As we go from the position of *Ca* horizontally and vertically, we reach elements that are progressively of less and less importance on account of the diminution in intensities and decrease in the number of lines; and these peculiarities are found both in solar and in stellar spectra. To the right of *Ca* in the table are found *Sc, Ti, V, Cr, Mn, Fe, Co* and *Ni,* all represented by numerous strong lines both in chromosphere and in Fraunhofer spectrum. Vertically above *Ca* is *Mg,* and below it are *Sr* and *Ba,* all important elements in solar investigations. In column I, of the alkali metals, the only element represented in the chromosphere is *Na,* where it is found with less prominence than in the Fraunhofer spectrum. *He* is the only element in column

PERIODIC TABLE OF THE ELEMENTS

In italic figures are given the total number of lines for each element found in the chromosphere.

	0	I	II	III	IV	V	VI	VII	VIII
1.H 1.008 *35*									
	2.He 4.0 *15*	3.Li 7.0	4.Be 9.1	5.B 10.9	6.C 12.0 *160*	7.N 14.01	8.O 16.00	9.F 19.0	
	10.Ne 20.2	11.Na 23.00 *3*	12.Mg 24.32 *10*	13.Al 27.1 *3*	14.Si 28.3 *7*	15.P 31.0	16.S 32.07	17.Cl 35.46	
	18.A	19.K 39.10	20.Ca 40.1 *35*	21.Sc 44.1 *55*	22.Ti 48.1 *333*	23.V 51.2 *170*	24.Cr 52.0 *191*	25.Mn 54.9 *78*	26.Fe 55.8 *729* 27.Co 58.97 *102* 28.Ni 58.68 *146*
		29.Cu 63.56 *2*	30.Zn 65.38 *4*	31.Ga 69.9	32.Ge 72.5	33.As 74.96	34.Se 79.2	35.Br 79.9	
	36.Kr 82.9	37.Rb 85.45	38.Sr 87.63 *12*	39.Y 88.8 *48*	40.Zr 90.6 *127*	41.Nb 93.2 ?	42.Mo 96.0 ?	43. . . .	44.Ru 101.7 45.Rh 102.9 46.Pa 106.7
		47.Ag 107.88 ?	48.Cd 112.4 ?	49.In 114.8	50.Sn 119.0	51.Sb 120.2	52.Te 127.5	53.I 126.9	
	54.Xe	55.Cs 132.8	56.Ba 137.37 *11*	57–71 Rare Earths *233*	72. . . .	73.Ta 181.2	74.W 184.0	75. . . .	76.Os 190.9 77.Ir 193.1 78.Pt 195.2
		79.Au 197.2	80.Hg 200.4	81.Tl 204.0	82.Pb 207.1	83.Bi 208.0	84.Po	85. . . .	
	86.Nt 222.4	87. . . .	88.Ra 226.4	89.Ac 226	90.Th 232.2	91.Ux2 234	92.U 238.2		

O, the inert gases, that manifests itself in the flash spectrum.

Not only do the elements progressively differ from *Ca* in the prominence of their lines in solar and stellar spectra, but also in the manner in which the lines are enhanced in passing from the arc to the spark. Apparently, therefore, the explanation of these peculiar differences must be sought in the structure of the atom. Fortunately, as the result of a remarkable series of researches within the past few years, an adequate interpretation may now be given of this peculiar behavior of the elements. (See Chapter XVII.)

As mentioned above, the chromospheric and solar spectra agree exactly as to wave-lengths, but differ very greatly in the relative intensities of the lines. These differences of intensity are accentuated in the case of the "enhanced" lines, or those which are more intense in the spectrum of the spark than in the arc. The importance of enhanced lines in eclipse spectra was first recognized by Lockyer. The 1905 spectra confirm this important rôle played by the enhanced lines.

A comparison of the intensities of the lines in the Fraunhofer, chromospheric, arc and spark spectra forces one to the conclusion that while the Fraunhofer spectrum corresponds to the arc spectrum, the spectrum of the chromosphere more closely resembles that of the spark. The intensities of these four spectra have been compared in detail in *Astrophysical Journal, 39,* 166, 1914, and in the *Publications of the Leander McCormick Observatory,* volume II. The sun thus exhibits three distinct spectra under different conditions: the chromospheric spectrum, the Fraunhofer spectrum and the sun-spot spectrum. These three closely resemble the spectra of the stars α Cygni, Capella and Arcturus, respectively; α Cygni representing an "earlier" and Arcturus a "later" type of spectrum than that of the sun.

The following table, copied from the publication cited above, compares the heights in kilometers that the enhanced and unenhanced lines separately attain. The values are arranged according to the intensities of the lines in Rowland's tables, and they are divided into different groups. It is evident at a glance that the enhanced lines in all cases reach

Average Heights of the Chromosphere Arranged according to Intensities and Groups

	Solar Intensity 2 and Less				Solar Intensity 3 to 5				Solar Intensity 6 to 10				Solar Intensity Greater than 10			
	Total No. of Lines	Average Intensity Rowland	Average Intensity Chromo-sphere	Average Height	Total No. of Lines	Average Intensity Rowland	Average Intensity Chromo-sphere	Average Height	Total No. of Lines	Average Intensity Rowland	Average Intensity Chromo-sphere	Average Height	Total No. of Lines	Average Intensity Rowland	Average Intensity Chromo-sphere	Average Height
				km				km				km				km
Fe-group— All lines	240	1.26	1.07	338	243	4.18	1.82	505	116	7.42	3.54	512	23	20.5	6.9	789
Enhanced lines only	7	1.36	3.14	409	7	3.86	9.43	728	2	6.5	11.	650	......	......	......	......
Unenhanced lines	233	1.26	1.01	336	236	4.19	1.59	395	114	7.43	3.41	510	23	20.5	6.9	789
Ti-group— All lines	275	1.07	1.30	385	132	3.79	4.23	588	20	7.45	12.45	1690	8	19.6	27.5	3712
Enhanced lines only	44	1.30	2.78	484	45	4.87	7.94	639	6	8.17	28.0	4350	3	17.3	38.3	6333
Unenhanced lines	231	1.03	1.02	366	87	3.75	2.31	562	14	7.14	5.8	550	5	21.0	21.0	2140
Rare earths — All lines	150	0.82	3.10	417	29	3.59	6.15	783	2	6.5	7.0	625	......	......	......	......
Enhanced lines only	11	1.41	4.28	619	7	3.59	12.29	1464	......	......	......	......	......	......	......	......
Unenhanced lines	139	0.77	3.01	401	22	3.59	4.21	566	2	6.5	7.0	625	......	......	......	......

greater elevations than do the lines unenhanced. The importance of this fact cannot be over-emphasized. On account of the great elevations attained above the photosphere, the atoms forming the enhanced lines are found in different conditions of temperature, electrical excitation and pressure. According to Schwarzschild, there is little change in temperature as moderate heights above the photosphere are reached, the gases being practically in a state of thermal equilibrium. The changes in pressure, however, with changes in elevations are very great. The conclusions seem to be unmistakable that the greatly reduced pressures consequent upon the increased heights is the primary cause of the peculiar properties shown by the enhanced lines. Before following the matter through to this conclusion, it will be well to pass in review the salient facts of the remarkable work accomplished in the past quarter of a century on the structure of the atom. This will be done in another chapter (Chapter XVI).

Two notable additions to the information regarding the flash spectrum have appeared since the publication of the spectra secured at Daroca, Spain. These contributions have been by G. Abetti from spectra secured at the eclipse of August, 1914, and by H. C. Wilson from eclipse spectra taken June, 1918. These results confirm the 1905 spectra in their general features. Abetti's measures, however, show that the heights attained by the various gases in 1914 were different from those of 1905. These differences are indeed to be expected, for there are no reasons why gases subject to the violent commotions surrounding the sun should always attain the same heights. Similar changes in the depth of the absorbing atmosphere of the sun are found by Abbot in his investigations regarding the solar constant.

Valuable observations of the chromospheric spectrum were secured visually by Fowler in London during the progress of the *partial* eclipse of the sun, April 17, 1912. At its maximum phase, this eclipse was 0.91 total (the sun's diameter = 1.0). The 6-inch equatorial was employed in conjunction with the Evershed spectroscope, the observing conditions being very favorable. The number of bright chromo-

spheric lines that were seen vastly exceeded expectations. As early as thirty-five minutes before maximum eclipse, high-level chromospheric lines were noted at the cusps and the number of lines increased with the progress of the eclipse. During the maximum phase, hundreds of Fraunhofer lines were reversed, in fact the number of lines seen was so great that it was impossible to record all of the lines. The appearance greatly resembled the flash spectrum that had already been observed by Fowler at more than one total eclipse. About seventy bright lines between *b* and D were actually identified. That so many lines of the chromosphere were visible near the cusps at the time of the eclipse may be partially explained as the result of reduced sky illumination due to the fact that but twelve percent of the sun remained uncovered. A greater advantage may have resulted from the smaller effect of unsteadiness or " boiling " at the cusp as compared with the limb under ordinary conditions.

The success of these observations was so great that it seemed possible to Fowler that even better results could be obtained at a similar eclipse by the use of more powerful apparatus, and that the multitude of bright lines seen visually for half an hour, while the eclipse ranged from eight- to nine-tenths total, might profitably be photographed by suitably arranged instruments. In fact, at this same eclipse, Newall at Cambridge actually secured successful photographs. On the best photograph only about forty lines were recorded as bright, many of them exceedingly narrow with the continuous spectrum quite faint. Apparently, therefore, it is more difficult to photograph the bright lines than it is to observe them visually. In view of the success attained in photographing, Newall came to the conclusion[1] that " exceedingly valuable work could be carried out with an instrument of high power by an observer who, in a total eclipse, stationed himself to the north or south of the band of totality at such a distance that the maximum phase was about 0.99. At such a station, detailed observations could be conveniently made with a much more leisurely program and with far greater completeness than on the central line."

[1] *Monthly Notices, R. A. S., 72,* 538, 1912.

Observations similar in kind were also made visually at the same eclipse by Fathers Cortie and Rowland at Stonyhurst. A Browning spectroscope with a dispersion of eight prisms of 60° was employed, the region observed being in the green from 5167 A to 5400 A. " Every line in the field was reversed, the bright lines tapering to a point indicating decrease of pressure."

In view of their success in 1912, the Cambridge observers prepared to photograph the eclipse of 1921 with the McClean spectroscope of the Solar Physics Observatory. This instrument uses an image of the sun 168 mm in diameter, the dispersion being caused by a six-inch plane grating. Two photographs were secured with excellent definition — but the total number of bright lines visible was only two, due to hydrogen, not a single bright metallic line appearing on either of the plates. A similar disappointment resulted from the photographs taken with the Huggins refractor, also at Cambridge. No explanation can be given for the failure to photograph the bright lines. The observing conditions appeared equally good at the two eclipses, and the amount of obscuration in the years 1912 and 1921 was nearly the same, being 0.91 in the former and 0.89 total in the latter year.

As already stated, observations by the spectroscope of the flash spectrum at the beginning and ending of totality are capable of furnishing very accurate times of second and third contacts. Visual observations with the spectroscope can also be utilized to obtain the times of the beginning and ending of the partial eclipse, i.e., first and fourth contacts. The ordinary method of noting first contact directly by means of a telescope permits an observation only when the dark limb of the moon is actually seen to encroach upon the face of the sun. The time is accordingly always recorded too late, by amounts depending on the size of the telescope employed, the experience of the observer, etc. Fourth contact may be observed more accurately than first contact since the observer may watch the diminishing indentation on the sun's surface. At first contact, with the spectroscope and slit arranged in the ordinary manner for the

observation of the prominences, the C-line in the red may be observed at the expected point of contact. The instant when an indentation appears in this line is the signal for first contact. Fourth contact by this method can be similarly observed, but more accurately than first. However, in spite of the fact that this method should be capable of giving the contacts correct within one second of time, yet at the eclipse of April 17, 1912, the recorded times of Father Sidgreaves and Fowler, both using this method, differed by more than two minutes.

As a result of investigations of the chromosphere from spectra taken at the time of an eclipse it seems safe to make the following general conclusions:

1. Wave-lengths in chromospheric and solar spectrum are probably identical.

2. Every strong line in the Fraunhofer spectrum is found in the flash spectrum, and every strong line in the latter (with the exception of *H* and *He* lines) is matched by a line in the former.

3. The flash spectrum may therefore be regarded as a reversal of the Fraunhofer spectrum.

4. The "flash" is not an instantaneous appearance. At the beginning of totality the chromospheric lines of greatest elevation appear first, and at the end of totality remain the last.

5. The "reversing layer" which contains the majority of the low-level lines of the chromosphere is about 600 km in height.

6. The "reversing layer" has no existence separate from the chromosphere.

7. It is the densest part of the chromosphere lying closest to the photosphere, and it is the cause of the greatest portion of the absorption producing the Fraunhofer lines.

8. The "Evershed-effect" measured in sun-spots, and photographs of flocculi which exhibit vastly different aspects when photographed at various elevations above the photosphere prove that the shadings of such *strong* lines as H and K are caused by absorption at different levels and pressures above the photosphere.

9. The chromospheric spectrum differs greatly from the ordinary solar spectrum in the intensity of the lines.

10. The Fraunhofer spectrum is essentially an arc spectrum. The chromospheric spectrum more closely resembles the spark spectrum, and its spectrum corresponds to an "earlier" type than that of the sun.

11. Especially prominent in the chromosphere are the enhanced lines.

12. The enhanced lines ascend to greater elevations above the photosphere than do the ordinary lines.

13. The increased elevations cause greatly diminished pressures.

14. As Saha has shown, the reduced pressures permit the ionization of the atom. As a result, the lines of the ionized atoms are specially prominent in the flash spectrum. The enhanced lines are produced by the ionized atoms.

15. The depth of the chromosphere is not constant.

The mode of attack for future eclipses can be definitely outlined: To be of the greatest value, flash spectra should be secured with large dispersion, they should extend as far into the violet and as far in the red as possible, the definition should be of the very best and the exposures should be timed so as to photograph the very lowest possible levels. The occupation of a station near the edge of the moon's shadow path would permit relatively long exposures on the low-lying layers closest to the sun's pole. Such spectra would afford interesting comparisons with those taken near the central line of totality which give spectra near the sun's equator. Another important investigation for the future will be to make comparisons between flash spectra taken at different phases of the sun-spot period. If we are to judge by the changes which take place in the spectra of the corona, we should expect that the flash would be richest in lines at times of maximum sun-spots. The eruptions taking place near spot zones seem to elevate the low-lying metallic vapors. If this be true it would be natural to expect that if it were possible to photograph at a constant level above the photosphere, in securing the flash spectrum at an eclipse,

then more lines should appear at sun-spot maximum than at minimum. It will consequently be interesting to compare the flash spectra of 1923 near spot minimum with those of 1905 taken near maximum of spots.

The best photographs of the flash spectrum at future eclipses will probably be obtained by the use of a concave grating without slit.

Early in the year 1909, Evershed announced a remarkable discovery of far-reaching importance in his observations of the displacement of Fraunhofer lines in the penumbra of sun-spots. With the slit of his spectrograph placed across a sun-spot, he found that the wave-lengths of lines in the penumbra of the spots were different from the values at the center of the sun. The displacements, which effected practically all of the lines of the reversing layer, were not constant but differed in amount depending on the intensity of the lines investigated. The shift was greater for the weaker lines of the spectrum than it was for the stronger lines. Evershed advanced the hypothesis that the observed displacements are the result of the Doppler effect, and that in consequence, the gases of the reversing layer are in radial motion tangential to the solar surface.[1]

Following the announcement of this important discovery, St. John began an extended series of investigations into the subject, the results of the observations being published in the *Contributions from the Mount Wilson Observatory*, Nos. 69, 74 and 88. The observations were carried out by photography with the 60-foot tower telescope, with the image of the sun 170 mm in diameter, the penumbra of the spots investigated averaging 3.0 mm in diameter. The plates in the violet and green were taken in the third order spectrum, and those in the yellow and red in the second order. For the two cases, the dispersion was 1 mm = 0.56 A and 1 mm = 0.86 A, respectively. Measures were carried out on 506 lines, some of the lines being measured on no less than thirty plates.

[1] *Kodiakanal Observatory Bulletin*, No. XV; *Kodiakanal Observatory Memoirs*, 1, Pt. 1.

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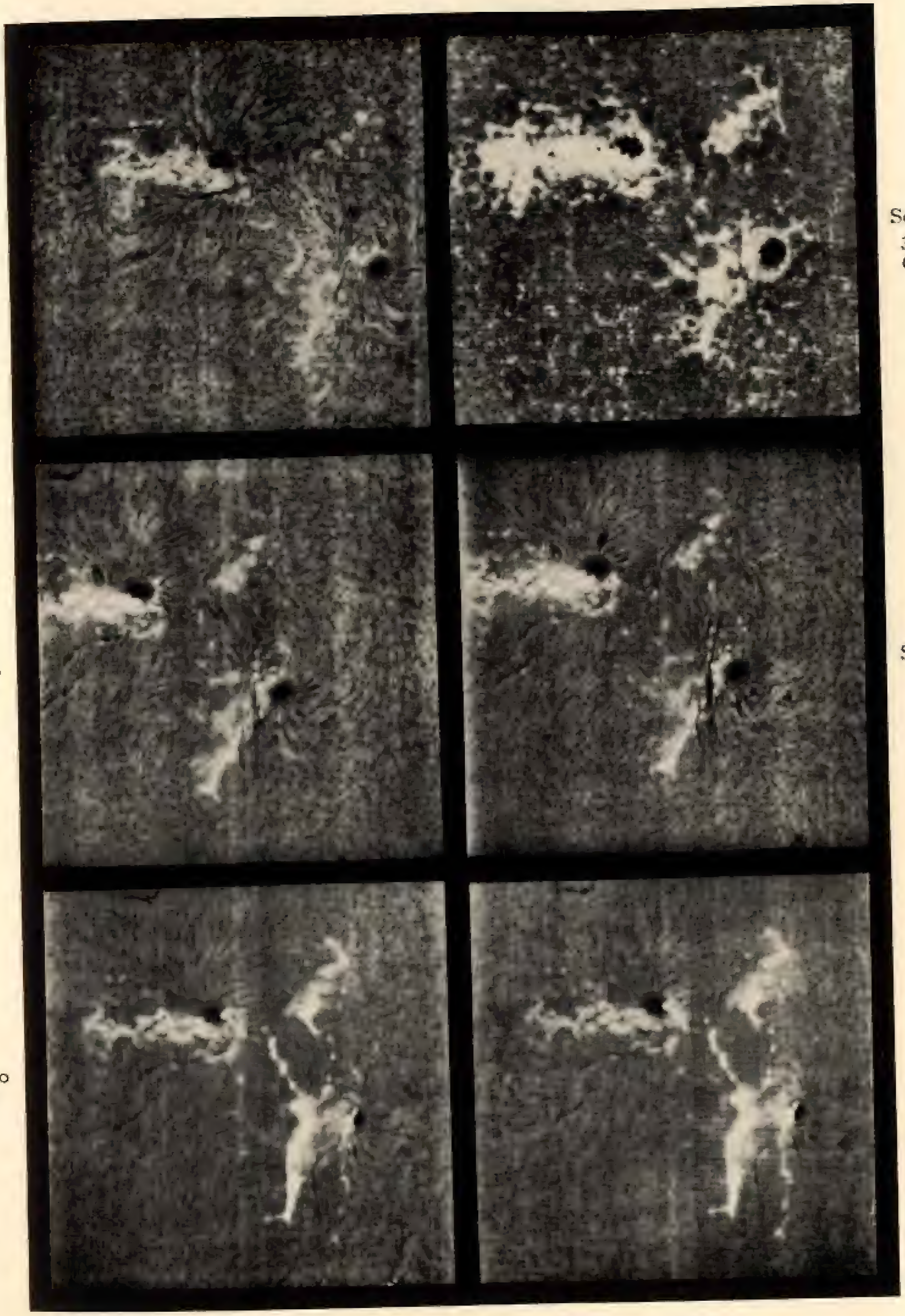


Eruptions Connecting Sun-Spots, Sept. 9–10, 1908

Photographed with Yerkes Refractor by Fox and Abetti. These spectroheliograms show changes taking place in a comparatively brief time. All photographs, but one, obtained with hydrogen light.

The Mt. Wilson measurements, so carefully made by Miss Ware, abundantly verified Evershed's conclusions that the displacements are caused by movements of the solar vapors tangential to the solar surface and radial to the axis of the spot. These motions are none other than the actual flow of the material of the reversing layer *out* of the spots and of the matter forming the chromosphere *into* the spot vortex.

St. John made a detailed comparison of the Mt. Wilson measurements of the Evershed effect with the heights determined from the eclipse spectra of 1905 and reached conclusions of the very highest importance. On account of the richness of the eclipse spectra, the peculiarities of individual lines were averaged out, and the lines due to different elements could be considered separately. As iron is the element of the greatest number of lines in the flash and also in the solar spectrum, the information from iron lines is more complete than for the other elements. No less than 356 lines with no identification other than *Fe* appear in the flash spectrum. The first conclusion reached, in comparing the intensities of the flash lines with the observed heights, is almost self-evident, and that is, that the stronger the line the higher it extends above the photosphere. As a corollary (but not so obvious) is the conclusion that weak Fraunhofer lines originate at lower levels than do the stronger lines of the same element. By excluding the enhanced lines, the following tables give St. John's results for *Fe*, where the lines are classified according to their Rowland intensities:[1]

FE LINES AND LEVEL AS SHOWN BY FLASH SPECTRA

	Number of Lines									
	4	19	30	55	72	49	40	28	24	25
Solar Intensities	00	0	1	2	3	4	5	6	{7–8–9 (7.8)	{10–40 (16.4)
Flash Intensities	0.25	0.26	0.33	0.8	1.4	1.6	2.0	3.5	3.8	7.0
Heights in km	275	279	288	344	369	397	425	488	590	806

1 *Mt. Wilson Contributions, 88,* 1914.

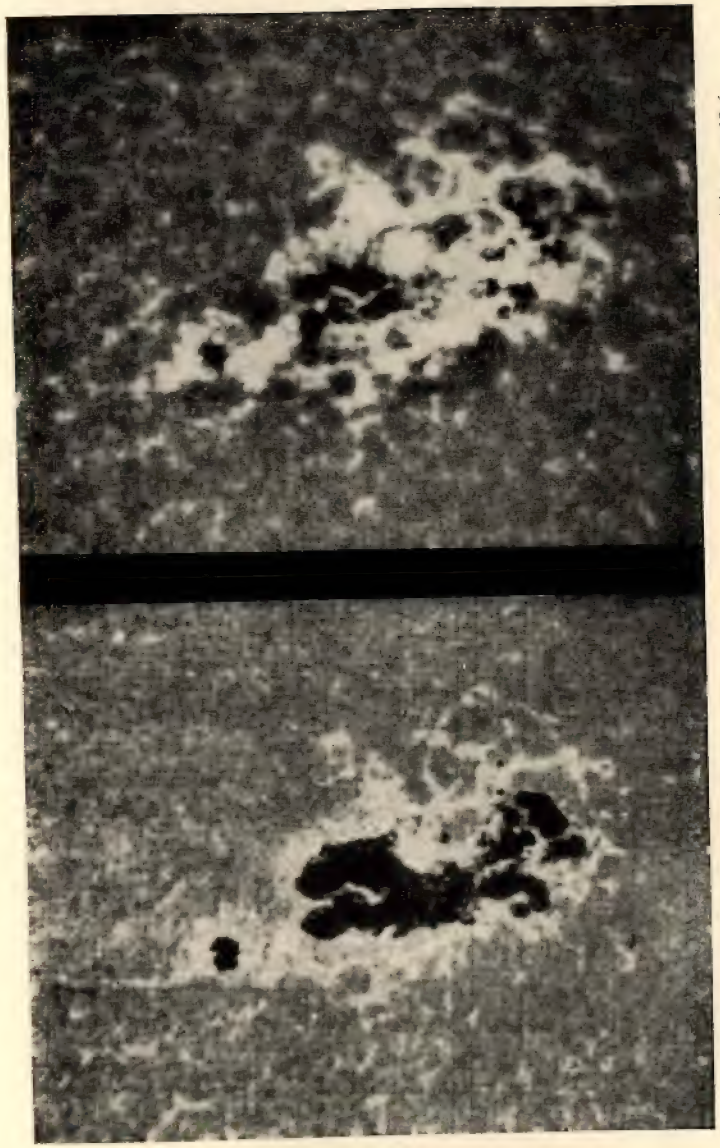
Similar results are found by considering other elements separately, such as *Ti*, *C*, etc. As a consequence of these tabular values, it seems impossible to come to any conclusion other than that a line of *Fe* of Rowland intensity 0 takes its origin at a lower level than a line of intensity 4, and in turn this line is found to originate below a line of intensity 10. If now the Evershed displacements are compared with the foregoing table, we reach some interesting results, as given in the following table:

HEIGHTS AND RADIAL DISPLACEMENTS OF IRON LINES

Solar Intensities	00	0	1	2	3	4	5	6	7–9	10–40
Heights	275	279	288	344	369	397	425	488	590	806
Displ. in wave-length	+.034	.030	.028	.025	.023	.021	.019	.016	.010	.002
Displ. in km	2.0	1.8	1.7	1.5	1.4	1.2	1.1	1.0	0.6	0.1

The displacements are measured in units of wave-lengths, or angstroms, and in kilometers per second, and the + sign signifies that the vapor is moving *out* of the sun-spot. Similar results are obtained from the other elements considered. It is readily seen, therefore, from the above table, that the iron vapor causing the weak, low-lying lines of the spectrum has a movement out of the spots that is greater in amount than the motions of the vapors at greater altitudes above the sun's surface. The motions measured in kilometers per second are obtained by multiplying by 60 the displacements in wave-lengths.

The layers closest to the sun's surface have a motion of translation out of the spot at the rate of two kilometers per second, and this motion becomes less and less at greater and greater elevations until, at a height of about two thousand kilometers, the motion outward of gases from the sun-spot ceases. What happens to the vapors above this level? The information furnished by the investigations of St. John is very definite and apparently admits of no contradiction. Above this level of inversion, the gases of the chromosphere take a motion carrying them *in* to the spot. As greater and greater elevations are reached these movements increase in amount. At the maximum heights reached by lines of the



Calcium Flocculi, Middle H_1 level. Slit at 3966 A Calcium Flocculi, H_2 level. Slit at 3968.6

THE GREAT SUN-SPOT OF OCTOBER 9, 1903

(For Comparison with the Stereoscope)

chromosphere, which are attained only by the H and K lines of the element *Ca*, there is a movement of the calcium vapor into the spot at a speed of 3.8 km per second corresponding to a displacement measured by St. John of –0.063 angstroms.

In the following table there is collected the available information from the measures of heights derived from 2841 lines in the flash spectrum and of displacements due to the Evershed effect from 506 lines in the penumbra of sun-spots. The + symbol affixed to an element, as *Ca+*, signifies that the line in the spectrum is enhanced and that it takes its origin from the ionized atom.

Heights and Displacements from Evershed Effect

Height in Kms from Flash Spectra	Element	Evershed Displacements in Km
14,000	*Ca+* (H and K)	– 3.8
(10,000)	$H\alpha$	– 3.0
8,500	$H\epsilon$, $H\zeta$	
8,000	$H\beta$, $H\gamma$, $H\delta$, *He*	– 1.1
7,000	*Mg*	– 0.7
	Sr+	– 0.1
6,000	*Ti+*, *Sc+*	*Sc*, + 0.9 (?)
	Fe (15–40)	0.0
5,000	*Ca* (4227)	– 0.2
2,000	*Al*	0.0
	Fe (10)	+ 0.2
1,000	*La*, *C*, *Y*, *Fe* (6)	*Fe* (6), *Ca* (6) + 1.0
	Ce, *Er*, *Eu*, *Gd*	*Fe* (4) + 1.2
500	*La*, *Nd*, *Pr*, *Sa*	
	Sc, *Y*, *Fe*	*Fe* (00)+ 2.0

It is evident, from a glance at the above table, that the enhanced lines not only extend to greater elevations than do the unenhanced lines of the same element, but that the Evershed effect for them is more pronounced as well. As already stated, the increased heights to which these vapors ascend correspond to greatly diminished pressures. The enhanced lines of any particular element are comparatively few in number. Likewise the total number of atoms of any chemical element ionized must always be a very small percentage of the total number of atoms. If therefore in the

above table, we take regard only of the ordinary neutral atoms, or those which have not lost an electron, it is seen that the vapors in the solar atmosphere arrange themselves more or less in layers according to their atomic weights. The lightest gas, hydrogen, extends to the greatest heights shown by any neutral atom, and next to hydrogen in elevation comes helium. Next in elevation to *H* and *He* come the heights attained by *Mg*, the strongest *Fe* lines and the 4227-line of neutral *Ca*. Thus the neutral atom of *Ca*, as well as the $Ca+$ atom, give a specially prominent place in the periodic table of elements to calcium. The strength of the lines in the solar and in the flash spectrum, as well as the heights attained by both the neutral and the ionized atom of *Ca* are greater than one would expect *a priori* from the position of this element in the periodic table.

If now attention is centered on the elements of greatest atomic weight, we find in the flash spectrum no lines belonging to *U* (238), *Ra* (226), *Pt* (195), *Ir* (193), *W* (184), *Hg* (200) (the numbers in parentheses representing the atomic weights). In fact there is no element found in the flash with an atomic weight greater than 167. If any of these heavy elements are present in the sun (and there is every reason to believe that they *are* in the sun), they must exist only in the strata lying closest to the photosphere. In fact, this layer must be below the lowest layer caught by the flash spectrum photographs. The heaviest elements *actually* found in the flash spectrum are barium (at. wt. 137), and a number of the rare earths, *La, Ce, Nd* and others, with atomic weights between 139 and 167. In fact, *Ba* and the rare earths are the only elements with atomic weights greater than 91 that are discovered with certainty in the flash. It is evident, therefore, that the gases surrounding the sun arrange themselves more or less in concentric layers, the heaviest gases reaching very low elevations and the heights attained increase for lighter and lighter gases. For the neutral atom, the greatest levels are reached by the element of least atomic weight, hydrogen, while for the ionized atom, the element *Ca* reaches heights even greater than those attained by neutral hydrogen.

The distribution of gases surrounding the sun is quite analogous to conditions of the terrestrial atmosphere.[1] Closest to the earth's surface, extending upwards about 3 kilometers, is the region of storms and turbulent convective currents. Above this stratum is a region of comparative tranquillity attaining heights of 10 km. Still above this is a region of a uniform or inverted temperature gradient. The constitution of this outer envelope becomes simpler and simpler as great elevations are reached, and at a level of 100 km above the earth's surface, the atmosphere consists almost exclusively of hydrogen with a slight admixture of helium. The movement of gases in terrestrial cyclones and tornadoes resembles the motions in the vortices of sun-spots. It is therefore quite possible to gather information regarding conditions close to the sun by studying the details of terrestrial meteorology. We must however face the startling fact that we probably possess much more definite information regarding the distribution and motion of gases in different levels of the sun's atmosphere than we know of the terrestrial atmosphere outside of these layers lying closest to the earth's surface. Consequently, instead of the astronomer going to the meteorologist for information, it is much more likely that the officials of the government weather bureaus can study with profit the change in the conditions taking place in the sun's atmosphere. Already the meteorologist has had valuable information furnished him by the astronomer which has been put to profitable use in weather forecasting. Abbot's epoch-making work on the "solar constant" has shown that the amount of the sun's heat which reaches the outermost confines of the earth's atmosphere is not a constant, but varies as much as ten per-cent in its amount. The Weather Bureau of the Argentine Republic is utilizing these solar constant values furnished by Abbot for the purpose of predicting the weather, and the success attained has been quite remarkable.

Eclipse spectra add their quota of information to the question of the depth of the reversing layer which is effective in producing the Fraunhofer lines. According to St.

[1] St. John, *Mt. Wilson Contributions*, No. 74.

John (*Contributions from the Mt. Wilson Observatory*, No. 88), "The effective level of a line may be defined as that portion of the entire depth of a vapor that is mainly concerned in the production of a line. The light in a Fraunhofer line of intensity 4, for example, comes from a lower depth than in a line of intensity 10 because of the greater selective absorption in the latter. The light from the photosphere and from the lower, hottest layers of the vapor under consideration is selectively absorbed in both instances and fails to reach the surface, so that the emitted light of the respective wave-lengths comes from more or less sharply bound shells of vapor having a larger radius for the line of intensity 10 than for a line of intensity 4.

"The idea of effective levels has been tacitly employed, though not so definitely expressed in all spectroheliograph work. There is no question among solar physicists but that the light employed in $H_3 - K_3$ photographs comes from the highest level when a very narrow slit is used, that light forming the $H_2 - K_2$ photographs comes from a lower level, but not from the lowest levels; these are successively reached by setting the slit on the broad $H_1 - K_1$ shading at increasing distances from the center of the line. It is clear that here we are dealing with successive shells of calcium vapor. It is probable that a similar succession of shells would obtain for the calcium lines of decreasing intensities such as 4227, etc., and that is what appears in the radial displacements and in the heights from the flash spectrum when a sufficient number of lines is present to obtain means of weight."

It has been generally assumed by spectroscopists that the broad shadings of H and K in the solar spectrum are caused by increased pressures in low-lying vapors of the H_1 and K_1 levels. No other solar lines exhibit these shadings. It is not necessary to assume that the H_1 and K_1 levels are found at greater pressures and consequently that they originate below other low-lying vapors, but rather that the shadings are the effect of contrast due to the very great strength of H and K. Apparently, therefore, it is necessary to conclude that the whole of the reversing layer from the very lowest

Slit set at

3968.6

3968.2

3967.8

3966.4

3965.0

CALCIUM FLOCCULI PHOTOGRAPHED BY FOX WITH THE 40-INCH YERKES REFRACTOR, AUGUST 25, 1904

The slit was set at different wave-lengths corresponding to different levels above the sun's surface. Order: from lowest upwards.

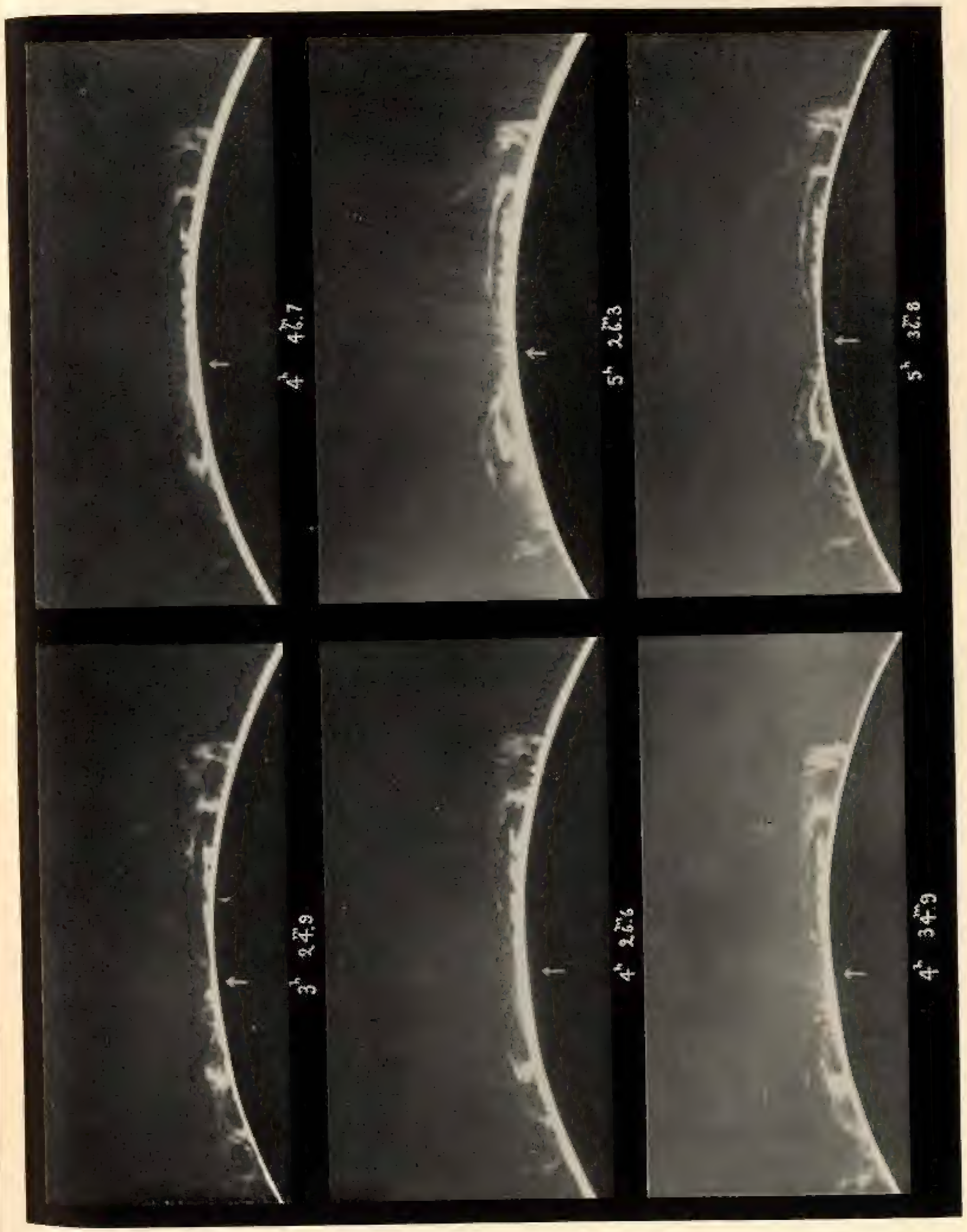
depths to heights of 14,000 km takes part in the absorption of light that produces the H and K lines in the Fraunhofer spectrum. Some have assumed that a relatively shallow layer only is effective in producing the Fraunhofer absorption. If we assign different wave-lengths to the lines $H_1 - K_1$, $H_2 - K_2$, and $H_3 - K_3$ due to calcium, we can, if we please, assume that the layers effective in producing these different wave-lengths are relatively shallow in each case. It will probably be simpler to assume that the *Ca*-atoms producing the whole of H and K by absorption are under a great variety of conditions of temperature and pressure that will, in consequence, give rise to wave-lengths which vary by appreciable amounts. However it will be necessary to assume that all of the atoms in the different layers are effective in producing the *total* absorption shown by the wide and strong H and K lines.

The shadings of H and K are not present in the flash spectrum photographs, although layers at all levels are effective in producing emission. The reason for the lack of definite shadings apparently is due to the fact that the level of the flash spectrum photographs was at an elevation above the low-lying layers where the Fraunhofer shadings for H and K are formed.

Eclipse spectra, taken in connection with the Evershed displacements, can shed some light on the problem of sunspots, not only regarding the time-honored question of the heights above the photosphere at which the spots themselves originate but also regarding the magnificent work of Hale on spot vortices. After long years of uncertainty regarding the effective temperature of spots, whether they are hotter or cooler than the photosphere, we have finally come to the conclusion that the spots are relatively cooler. This fact first became known through the discovery by Fowler of bands in the red part of the spectrum due to titanium oxide. Bands and flutings of hydride compounds have likewise been found in parts of the spectrum other than the red. There seems only one explanation possible, which is that the compounds can exist only at the cooler temperature of the

spots, and that at the higher temperatures of the photosphere the compounds are dissociated and their bands cease to show. All of the researches concerning spots confirm this view of cooler temperatures, the low-temperature furnace lines being strengthened and the high temperature enhanced lines being weakened in spots.

If we are to accept the explanation of the Evershed displacements that they are a Doppler effect which differs for lines of various solar intensities, which in turn depend on the depths at which these lines originate, then we can have no faith in the original idea of Wilson that spots are saucer-like depressions in the photosphere. If we admit such depressions as possible, we can readily see the consequences demanded in sun-spot spectra. Confine our attention to an *Fe*-line in the spectrum of intensity 4 in the photosphere. As this line is followed across the penumbra of the spot and into the umbra, where lower and lower levels are presumably reached, the intensity of the line should diminish in consequence of the lower levels attained at the bottom of the spot saucer. According to the table on page 247 it would need a change of only about 100 km to diminish the intensity of the spectral line from 4 to 1; the line thus being changed in intensity and becoming much weaker in the spot umbra. No such effect is visible. Other objections to the Wilsonian hypothesis based on the Evershed effect will readily appear to anyone. Consequently, it must be assumed that if there is any difference in level between the umbra of the spot and the general level of the photosphere that difference must be very small. It seems difficult to think of the spots being found *above* the general level of the photosphere. If there are any differences in level between the spots and the photosphere, the probabilities favor the view that the level of the spots is lower than the photosphere and not higher, but the lowest depths in sun-spots can differ very little from the lowest levels of the reversing layer. The difference in level cannot be as much as 50 km.



ATTRACTION OF SUN-SPOTS FOR PROMINENCES

Photographs by Slocum with Yerkes refractor. Arrow indicates sun-spot, and the changes at the times given may be noted.

CHAPTER XV

ECLIPSE SPECTRA AND RELATED SOLAR PROBLEMS

THE conclusions drawn from eclipse spectra that strong lines originate at higher levels above the sun's surface than do lines less intense have very important consequences in the problem of the period of rotation of the sun. The determination of this rotation by spectroscopic methods is one of the very greatest perplexity and still awaits an adequate solution. The information drawn from direct observation of sun-spots was positive enough as far as it went. At the equator on the sun, spots take about twenty-five days to make a complete circumference, while at latitudes north and south, the sun rotates more slowly, a day longer being required for a spot at 30° than at the equator. On the whole, the information from spots furnishes contradictory conclusions since the individual spots have peculiar motions of their own which are not representative of the general surface of the sun. Few spots appear at distances greater than 40° from the sun's equator, and manifestly it is impossible to determine the law of rotation in high latitudes where observations on spots are impossible.

With the application of the spectroscope and the photographic plate to the problem, it was confidently expected that all difficulties would disappear, since the measurements were henceforth to be made on sharp and well-defined Fraunhofer lines. All that seemed necessary for a complete solution of the problem was to utilize a spectroscope of sufficiently high dispersion so that the shift in wave-length due to rotation could be measured with an adequate degree of precision. The great advantage of the spectroscopic method was that the observations might be carried out at any time without waiting for the appearance of a spot. A still greater ad-

vantage, however, was that observations were not confined to the zones of sun-spots, but could be pushed even to the sun's poles. At the solar equator, the eastern limb advances at the rate of 2.0 km (1.2 miles) per second, while the western limb recedes at the same rate.

From observations of spots, several different empirical formulas have been devised to represent the rotation of the sun at different latitudes. Chief among them may be mentioned those of Carrington and Faye. The latter has usually been regarded as the most satisfactory formula, and to it spectroscopic observations closely conform. Faye's equation may be readily adopted for spectroscopic work and takes the form [1]

$$v + v_1 = (a - b \sin^2 l) \operatorname{Cos} l$$

where v is the velocity in the line of sight deduced from the actual observations; v_1 is a correction allowing for the orbital revolution of the earth so as to convert synodic periods to sidereal; l is the latitude of the region on the sun under investigation; and a and b are velocities measured in kilometers (or miles) per second. It has been assumed that a and b are constants, or, in other words, that the sun's rotation is not varying. If b is equal to zero, then the sun would rotate like a solid sphere with equal angular rotations in all solar latitudes.

The first spectroscopic observations for determining solar rotation are now thirty-five years old, and were made by Dunér of Upsala. Two lines were chosen in the red and their wave-lengths were compared with terrestrial lines which consequently show no rotational shift. The measures were carried to within fifteen degrees of the poles of the sun. Since the date of the original work done at Upsala, observations have been in progress continuously for a period of more than twenty years. The values published [2] for the linear velocity at the solar equator are:

[1] Newall, *Monthly Notices, R. A. S., 82*, 101, 1921.
[2] *Report of the Committee on Solar Rotation*, 1922 meeting of the International Astronomical Union.

LINEAR VELOCITY OF SOLAR ROTATION AT THE EQUATOR

Observe	Location	Velocity km/sec.	No. of Lines	Region	Date
Dunér	Upsala	2.08	2	6301–6302	1900.5
Halm	Edinburgh	2.04	2	6301–6302	1904
Adams	Mt. Wilson	2.06	20	4196–4294	1907
Adams	Mt. Wilson	2.05	22	4196–4291	1908.5
Storey and Wilson	Edinburgh	2.08	10	6280–6318	1909
Plaskett, J. S.	Ottawa	2.01	19	5506–5688	1911
Plaskett, J. S.	Ottawa	2.02	15	4196–4291	1911
De Lury	Ottawa	1.97	19	5506–5688	1911
Hubrecht	Cambridge	1.86	40	4299–4400	1911
Plaskett, J. S.	Ottawa	2.01	27	4250 and 5600	1911–12–13
Schlesinger	Allegheny	2.00	20	4058–4276	1912
Evershed and Royds	Kodaikanal	1.95	—	3906 and 5624	1913
Plaskett, H. H.	Ottawa	1.98	12	5576–5628	1913
St. John and Ware	Mt. Wilson	1.94	35	4123–4338	1914
Plaskett, H. H.	Ottawa	1.95	5	5900–	1915
St. John and Ware	Mt. Wilson	1.94	26	5018–5316	1914–18
St. John and Ware	Mt. Wilson	1.95	7	6265–6337	1916–17

After the expenditure of so much time and energy on this research it must be confessed that the results attained are a grave disappointment. A glance at the velocities at the equator given in the above table will reveal values ranging from 1.86 to 2.08 km per sec. The measures were carried out very carefully, using every precaution to free them from errors. Each of the results in the above table is the mean of a very great number of observations on many different spectrum lines (in one case numbering forty), and it would seem as a consequence, that the measures should have a high degree of precision with the final values entirely free from systematic errors. The simplest explanation of the divergent results would appear to be that the sun must be changing its speed of rotation; but the range of ten per cent of the whole value is surprising, to say the least. Unfortunately for the precision of the results, the wave-lengths of lines in the spectrum have not the constant values originally supposed to exist; and to the many variations already known, eclipse observations add another, viz., that the stronger spectrum lines occur at higher levels in the sun and must therefore display greater velocities of rotation.

It is manifest that if the observations of one observer are to be compared with those of another, it will be necessary to subject the lines to a number of refinements as follows: (1), Only lines with well-determined wave-lengths should be employed, they should not exhibit any "pole-effect," and to be representative lines they should not be "enhanced;" (2), lines of like Rowland intensities only should be used; (3), lines of the same region of the spectrum only should be utilized since we are enabled to see into the sun to greater depths in the violet than in the red, this being due to the scattering of light. These conditions will limit very materially the choice of available lines.

Spectroscopic observations are ordinarily made at both ends of a solar diameter, the differential measures giving twice the value of the displacement. In order to eliminate any local effect at the limb due to the near presence of spots, faculae or filaments, it would be well to compare wave-lengths at the sun's edge with those at the center. The investigations of St. John[1] show that the wave-lengths of lines at the center of the sun are "constant to a surprising degree of accuracy." Newall recommends the method now on trial at Cambridge, of making the measures of displacements between east and west points on fixed chords, parallel to and equidistant from the projected axis of solar rotation, the east and west points being chosen in the same heliographic latitude, in either northern or southern hemisphere. This method is essentially one of comparing the law of solar rotation with the simple law of uniform rotation of a solid body. The method has some advantages over that ordinarily in use, and some disadvantages. The peculiarity of this method is that the spectra are taken on the bright parts of the sun's surface and not near the fainter limb. The work of De Lury has shown that wave-lengths determined at the limb are subject to slight uncertainties due to the superposition of the sky spectrum. If the photographs are taken through thin haze, the wave-lengths may be displaced by amounts depending on the strength of the solar lines investigated.

[1] *Mt. Wilson Contributions*, No. 223, 1922.

The discussions by Newall[1] and by Halm[2] of recent spectroscopic observations have led to interesting conclusions. The method usually followed by spectroscopists is to secure observations on as many days, at as many different solar latitudes as possible. When sufficient material is obtained, the velocities in the line of sight being found, they are then subjected to a discussion by least squares in order to determine the best possible values of the constants a and b in Faye's formula above. The different values of a, the velocity at the equator, obtained from various series of observations are listed in the table.

It might be said, in passing, that if ever in the history of spectroscopic work positive and conclusive results were promised by any piece of astronomical research, the chances were very great that such results could be positively assured beforehand by the investigation on the rotation of the sun by spectroscopic methods.

In the series investigated by the different observatories, various spectral lines and regions of wave-lengths were employed. In spite of the possible sources of error to which the measures were subject, it would seem, if more than a dozen or fifteen lines were measured in a certain series, that any local peculiarities of a single line should be certainly averaged out. From the nature of the problem, it seemed altogether probable that lines of approximately the same average Rowland intensity would necessarily be chosen by the different observers. Hence it might well have been expected that simultaneous observations of the sun made from different observatories would thoroughly agree in furnishing the same value of the solar rotation. How ideas have been changed in the past two decades regarding the constancy of wave-lengths! In comparing the longer series of observations, we have the results tabulated below, where are given all of the observations secured since the year 1906 as listed by Halm in *Monthly Notices*. In addition to the individual series secured at Edinburgh, Mt. Wilson and Ottawa, there is given the mean of all the values secured between the years 1901 and 1913, and also the results for

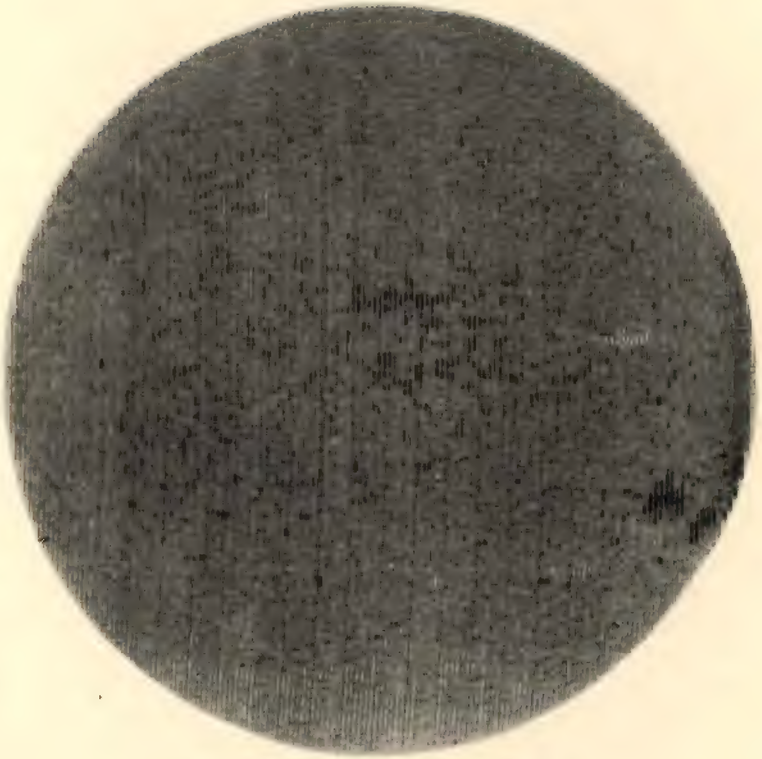
[1] *Monthly Notices, R. A. S.*, 82, 101, 1921.
[2] *Ibid.*, 82, 479, 1922.

the hydrogen line, *Hα*, obtained at Mt. Wilson. The velocities are given in kilometers per second for every five degrees of heliographic latitude.

LINEAR VELOCITIES OF ROTATION OF THE SUN

Helio-graphic Latitude	1906.3 Ed.	1906.4 Mt. W	1907.0 Mt. W	1908.5 Mt. W	1916.5 Ott.	1912.5 Ott.	1913.5 Ott.	1901.13 Mean	1908.5 Hα
0°	2.03	2.05	2.07	2.06	2.01	2.00	1.98	2.04	2.11
5	2.02	2.03	2.04	2.04	1.98	1.98	1.96	2.02	2.09
10	1.98	1.99	2.00	2.00	1.95	1.95	1.93	1.99	2.05
15	1.92	1.94	1.94	1.94	1.89	1.89	1.88	1.93	2.00
20	1.86	1.87	1.86	1.86	1.82	1.83	1.82	1.86	1.93
25	1.78	1.78	1.77	1.76	1.74	1.75	1.74	1.77	1.83
30	1.69	1.68	1.66	1.65	1.64	1.64	1.62	1.66	1.73
35	1.58	1.57	1.54	1.54	1.53	1.52	1.50	1.54	1.61
40	1.44	1.43	1.41	1.40	1.40	1.39	1.37	1.42	1.50
45	1.30	1.29	1.27	1.27	1.26	1.24	1.23	1.28	1.37
50	1.16	1.15	1.13	1.12	1.11	1.10	1.09	1.14	1.22
55	1.02	1.01	0.99	0.97	0.96	0.95	0.95	0.99	1.08
60	0.88	0.87	0.85	0.81	0.81	0.79	0.80	0.84	0.93
65	0.73	0.73	0.71	0.67	0.67	0.63	0.65	0.70	0.78
70	0.60	0.59	0.56	0.53	0.52	0.48	0.50	0.55	0.63
75	0.45	0.45	0.43	0.39	0.38	0.35	0.37	0.41	0.48
80	0.30	0.30	0.28	0.26	0.24	0.22	0.24	0.27	0.34

The following facts should be noted regarding the quantities in the table: (1), The values derived at Edinburgh agree perfectly with those taken almost simultaneously at Mt. Wilson; for among the seventeen separate linear velocities, only two differ as much as 0.02 km per second, showing a remarkable accord; (2), The three series at Ottawa are very consistent throughout all latitudes; (3), The three Mt. Wilson series found in the third, fourth and fifth columns agree perfectly among themselves between latitudes 0° and 45°, but show a progressive diminution of velocities at all latitudes poleward of 45°; (4), The Mt. Wilson *Hα* values are greater in amount than the Mt. Wilson results on the reversing layer for the year 1906.4, by an amount which is approximately constant and equal to 0.06 km per second; (5), The *Hα* values exceed the velocities of the three Ottawa series by a constant which amounts to 0.11 km per second; (6), The time of observations given in the Edinburgh and in the first Mt. Wilson column (1906.4)



TEST OF RADIAL MOTIONS IN THE SUN
Photographed by Deslandres at Mendon with the K1 ray of Calcium, April 11, 1910.

agrees fairly closely with sun-spot maximum, while the mean of the three Ottawa series differs little from sun-spot minimum.

On account of the splendid accord between the observations, we seem almost forced to conclude that the rotational velocity of the sun can be determined spectroscopically with great exactitude. The results tabulated above seem to prove most emphatically that at spot maximum the reversing layer revolves with a speed that is greater than the average, while at minimum of spots the rotational velocity is less than the average. This is the conclusion independently reached by Newall and by Halm.

There are two different ways of interpreting this important result. The simplest explanation seems to be derived by utilizing the results obtained from the $H\alpha$ series of Mt. Wilson. As known from eclipse spectra, this hydrogen line is found high above the reversing layer, and its greater rotational value is readily interpreted as being due to its elevation. This indeed is the conclusion reached by Adams in *Mt. Wilson Contributions,* No. 33. In the same publication, Adams draws attention to the fact that the calcium line 4227 A also shows greater velocities than do the average lines of the reversing layer. This *Ca* line takes its origin above the general reversing layer, but not as such great elevations as are reached by the $H\alpha$ line. As additional proof that the greater velocities attained by $H\alpha$ are caused by its elevation, measures were made by Adams of this line near the limb but projected on the sun's disk. Under these latter conditions, smaller values of rotation were secured. At the time (1908.5) when Adams secured the $H\alpha$ values, the sun was about midway between the epochs of maximum and minimum of spots, and hence it may be assumed that the sun was in approximately an average condition. If this be true, then we have the following differences in rotational values of the sun's equator measured in linear units of kilometers per second:

	Km/sec.
Difference between reversing layer at spot maximum and $H\alpha$	0.11
" " " " " " minimum and $H\alpha$	0.06
" " " " " " maximum and at minimum	0.05
" " " " and *Ca* 4227	0.075

To interpret the meanings of the above values, we seem forced to the conclusion that the greater rotational velocity at spot maximum is caused by the reversing layer being found at a greater elevation than at minimum. Consequently, if we knew the elevations at which *Ca* 4227 and *Hα* originate in the reversing layer above the level of the average gases, we should be in a position, from the above differences of velocity, to find the increase of elevation of the reversing layer at maximum over that at minimum. In the flash spectrum, *Ca* 4227 is found at an elevation of 5000 km, and *Hα* at 10,000 km. If we assume with St. John (*Mt. Wilson Contributions,* No. 40) that the Fraunhofer lines of *Ca* 4227 and *Hα* are formed at these same elevations, then we must also assume as a consequence that the reversing layer at spot maximum is from 3,000 to 4,000 km farther removed from the center of the sun than at spot minimum. Apparently, therefore, the greater activity of the sun at maximum carries the gases upwards to greater elevations than at minimum. The greater value of rotation at maximum being found at all latitudes is an indication that the effect is displayed over the whole sun. These conclusions seem quite plausible, — but let us see where this line of reasoning will lead.

From the above values, we see also that the linear velocity of the reversing layer at maximum exceeds that at minimum by 0.05 km per second, which is about one-fortieth of the velocity at the equator. But the region of the reversing layer is none other than the limb of the sun. Hence no other conclusion seems possible, if we are to admit the correctness of these numbers, than that the sun is larger in diameter at spot maximum than at minimum. However, no fact in astronomy is more positively known than that the sun cannot increase its diameter at maximum as much as one-fortieth, for this amount would correspond to a difference in the angular values of no less an angle than 48″.

There are methods of explaining the difference of rotational speeds at maximum and minimum of spots other than by assuming an increase in diameter of the sun at spot maximum, but each explanation leads to conclusions equally

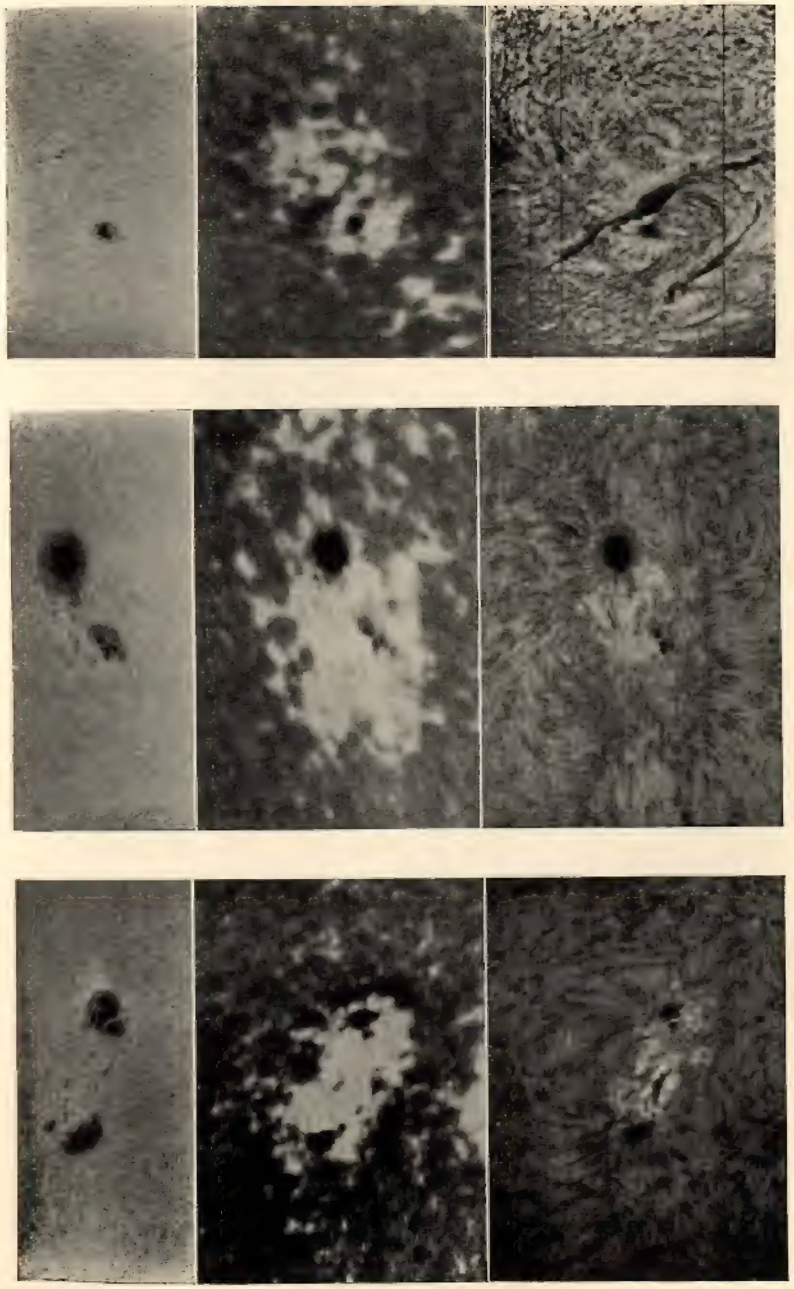
difficult to accept. Apparently, we seemed forced to the conclusion that, although there is such a beautiful accord between the measures listed in the above table, it may not be impossible that some of the observations may have been affected by errors, either accidental or systematic in nature, and that in consequence, the difference in rotational values at maximum and minimum of spots may be illusory and not real. For the reasons already stated, systematic errors due to different spectral lines investigated may readily find place in any series of measurements, and the only conclusion to draw from the large differences between Mt. Wilson and Ottawa is that one or both of these series of measurements are unquestionably affected by systematic errors. In fact, investigations made at Mt. Wilson, in which simultaneous observations are made upon the two limbs and the center of the sun, indicate that temporary and local conditions frequently exist in the reversing layer which produce differences of as much as ten percent on the rotation values obtained by comparing east and west limbs directly. Such results make it obvious that misleading values may be actually derived from a short series of observations; in fact it may be well to ask, along with the Chairman of the Committee on Solar Rotation of the International Astronomical Union "whether the solar rotation can be determined as definitely as has been thought."

The above discussion shows clearly, in spite of the apparent consistency of most of the series of values, that the measures unquestionably are subject to large systematic errors with the result that any conclusions from these observations regarding change in rotational value can have but little weight. An increase in rotational velocity at the equator of the sun can be caused only by the reason that the gases forming the general reversing layer (on which the measures are made) are at a greater distance from the center of the sphere of the sun. Expressed in other words, this means that the sun will be larger in diameter. If appreciably larger, it should be possible to detect the increase by measuring the angular diameter by the ordinary methods. This diameter is approximately 1920″. It is highly prob-

able that any change in this value must be less than a tenth of a single second of arc, otherwise it would have been detected in the splendid series of heliometer measures discussed by Auwers and by Schurr and Ambronn. An increase in the solar diameter by the amount of 1″ would be an increase of one part in 1920. As a consequence of such a great increase in the diameter of the sun, the equatorial rotation of the sun would increase 1/1920th part, or 0.001 km per second, a quantity so exceedingly minute that it cannot with certainty be detected by any spectroscope at present in existence. It is therefore not surprising to learn from the annual report for the year 1922 of the Director of the Mt. Wilson Observatory that, after a discussion of their observations carried through eight years on a consistent plan, there is no evidence of any change in the rotational velocity of the sun of a size that can be detected. It would therefore seem highly desirable that all of the observatories participating in the plan of measuring the rotation of the sun by spectroscopic methods might do well to thoroughly canvas the situation to see whether it is possible for them to detect any change in the sun's rotation, and whether it might not be better to devote some of their energies and equipment spent on this problem to another investigation that will promise more fruitful results. An exception should be made in the case of the Mt. Wilson Observatory which should unquestionably continue its measures through a complete eleven-year sun-spot cycle.

The red line of hydrogen having shown different rotational values from the other lines investigated, an attempt was accordingly made by Adams to secure better definition by means of stained plates. The photographs obtained were so greatly superior to the earlier plates taken that Hale was led to use the same plates in photographing the $H\alpha$ flocculi by means of the spectroheliograph. The results were a great surprise, for it was seen that the hydrogen flocculi differed from those taken by means of the H_2 line of calcium in several remarkable features.[1] The photo-

[1] *Mt. Wilson Contributions*, No. 26.



April 22, 1916

July 12, 1914

Sept. 9, 10, 1910

a b c

BIPOLAR SUN SPOTS

a. Direct photographs. *b.* K_2 spectroheliograms. *c.* $H\alpha$ spectroheliograms.

graphs of hydrogen flocculi already secured showed that they did not share the polar retardation in rotation shared by spots, faculae and calcium flocculi. But the striking differences between the details of the photographs of flocculi in the *Hα* light of hydrogen and in the H_2 line of calcium, when examined side by side, showed that whereas most of the calcium flocculi are bright, those due to hydrogen are dark. Further differences were exhibited by the accentuated definiteness of structure of the hydrogen photographs which show details much smaller in size and with greater distinctness. The details brought forth by the *Hα* line were more marked than those obtained by the other hydrogen lines *Hβ*, *Hγ* and *Hδ*, the reason for the difference being caused by the greater strength of the *Hα* line in chromosphere and prominences and the greater heights attained. A most unusual series of photographs was secured by Hale on June 3, 1908, showing a dark hydrogen flocculus which was actually seen drawn into a sun-spot vortex, the remarkable change taking place within the brief space of time of ten minutes. The day previous, the location of the flocculus was evident from local whirls. On the day following the disappearance of the mass of *cool* hydrogen into the spot, photographs were secured showing eruptions in the neighborhood of the spot due to *bright* and *hot* hydrogen gas. Apparently, therefore, a sun-spot is a vortex somewhat resembling a terrestrial cyclone. Relatively cool matter in the gaseous form, floating high above the solar surface, is sucked into the vortex with a whirling motion. After sinking into the interior of the sun, the cool gas is heated, and later in the heated state makes its reappearance outside of the limits of the spot, but in its immediate neighborhood. Moreover, since the appearance of the hydrogen flocculi surrounding the spot was seen to frequently resemble the distribution of iron filings in a magnetic field, it therefore seemed quite possible to Hale that observations carried out in an adequate manner might reveal the presence of a magnetic field connected with the spot.

The most promising method of attack appeared to be the Zeeman effect. When a luminous vapor is subjected to

a magnetic field by being placed between the poles of a powerful magnet, an effect is produced on the lines of the spectrum. If the radiation is observed *along* the lines of force, the spectrum lines appear in most cases as doublets, having components circularly polarized in opposite directions. It was found that different lines of the same element are affected to a different degree, and that the distance between the components of a given doublet is directly proportional to the strength of the field. In a field of moderate strength the distance between the two components of a doublet may not result in complete separation, the lines being merely widened, while in other lines, which are exceptionally sensitive, the separation may be complete. As early as 1892, Young with the Princeton refractor, and later W. M. Mitchell, observed lines due to iron in the sun existing as single lines in the spectra of the photosphere but double in spot spectra.

If, therefore, the observers at Mt. Wilson were to endeavor to find a magnetic field in sun-spots, the line of attack was clearly outlined. First of all, there was necessary a large image of the sun, possible only by the use of a telescope of great focal length so that the surface of the sun could be examined in regions surrounding the spot. The solar light must then be examined by a spectrograph of such great power that the separation of the doublets showing the Zeeman effect might be as great as possible. To interpret the measures of the solar photographs, investigations in the laboratory unquestionably would be necessary. Fortunately for the development of astronomical research, the resources of the Carnegie Institution were ample to provide on the top of Mt. Wilson, the 60-foot and the 150-foot tower telescopes with powerful spectographs attached, and to equip in Pasadena a physical laboratory with the necessary forms of refined apparatus. As the result of fifteen years of investigation, the scientific information garnered regarding spots and the general magnetic field of the sun has been very startling and most important.

In carrying out this investigation, a Fresnel rhomb and a Nicol prism are mounted above the slit of the spectroscope

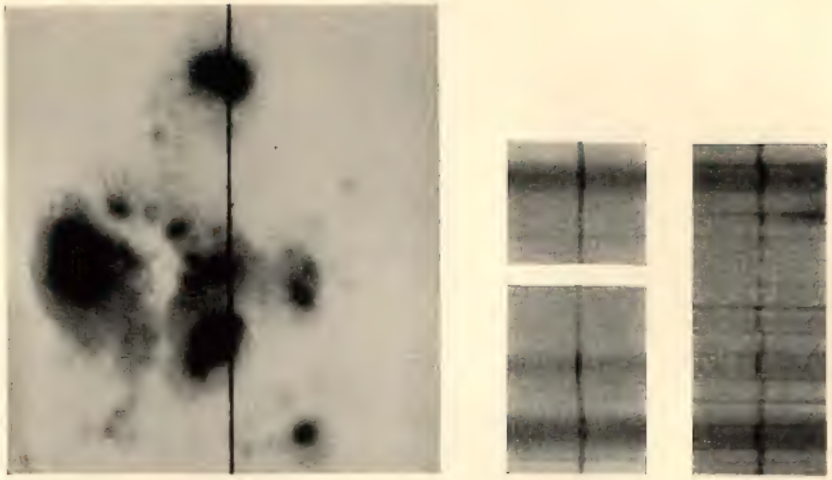
so that the light of the solar image passes through them. If the doublets in the spots are produced by a magnetic field, the light of their components, circularly polarized in opposite directions, should be transformed by the rhomb into two rays, plane polarized and differing 90° in phase. By a rotation of the Nicol, the intensities of the two components of the doublet will be altered. For instance, in a certain position of the Nicol, the light from the red component should be transmitted and that of the violet component cut off, while the Nicol rotated 90° should transmit the violet component and cut off the red component. It is hardly to be expected, however, that the extinction of either component will be complete. A partial extinction of the red or the violet component has the effect of shifting the maximum of brightness of the doublet towards the red or the violet of the average position, depending on whether the red or the violet component is the stronger. When the two components are not entirely separated, the lack of uniformity in the lines causes a displacement which depends on the relative strength of the two components. This unsymmetrical character of the lines renders the accurate measurement of the displacements one of the very greatest difficulty. In fact, even with the great scale of the Mt. Wilson photographs reliable measures are possible only on a comparatively small number of lines.

After these plans had been carefully formulated, a spot near the sun's edge soon gave Hale the opportunity of examining the effect on the spectral lines. Manifestly, if the Zeeman effect for a spot near the center of the sun's surface is along the lines of force, this effect must be at right angles to the lines of force when the spot has moved to the limb of the sun. Hale was therefore able to conclude that sun-spots possess magnetic fields and that the lines of force are directed nearly radially towards the center of the sun. These original conclusions have been abundantly verified by all later investigations. By a comparison of the separation of certain components in sun-spots with the separations obtained in the laboratory when investigating magnetic fields of different strengths, information has been

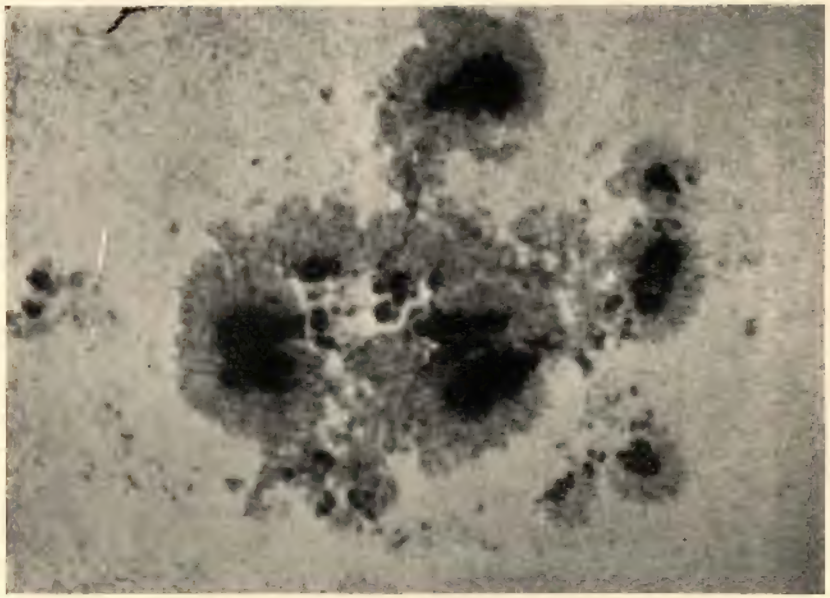
secured regarding the intensity of the magnetic field. In some cases field strengths in spots as great as 4500 gausses have been found.

The cause of the magnetic field shown in spots, now believed to be understood, is due to the electrons, or electrified particles, that exist in the solar atmosphere. The whirlpool or vortex motions exhibited by spots cause these electrified particles to partake of more or less circular motions. Such motions are similar in kind to that of an electric current moving in a coil of wire which is known to produce a magnetic field. Consequently, a sun-spot by its vortex motion appears to create its own field.

At times there are violent outbreaks near sun-spots, and if these take place when the spot is nearly central on the face of the sun, the lines of force proceeding from the spot are directed towards the earth. Under these circumstances, streams of electrified particles, or electrons, are discharged from the sun and reach the earth's atmosphere in great numbers. In the rarefied conditions existing in the upper atmosphere the air becomes ionized. This ionization causes the electromagnetic display known as northern lights, or aurora borealis. As a result of the electrification of the atmosphere, currents are induced in the earth, which may at times be so strong as to seriously interfere with the sending of messages over the telegraph lines or submarine cables. As a further manifestation of the currents flowing through the earth, the navigator's compass may be affected with the result that the north end of the needle may point several degrees from the magnetic north. This leads to a so-called "magnetic storm." The display of a brilliant aurora is almost certain to be accompanied (and caused) by a spot central on the face of the sun. On May 13, 1921, the spots near the sun's center caused an unusually gorgeous display of aurora visible practically all round the world. The telegraph lines were seriously hampered in the sending of messages. While the aurora was at its height, one of the Atlantic cables connecting Europe and America was burnt out. Whether this was caused by the earth's currents, or was but a strange coincidence, has never been fully determined.



a *b* *c*



d

a, b, c Photographic observations of a multipolar sun-spot group on August 8, 1917 at Mt. Wilson Observatory. *b* and *c* photographed with Nicol and quarter-wave plate shows the Zeeman effect with the iron triplet 6173 A.

d An enlarged direct photograph of the same spot group on August 6, 1917 with the 60-foot tower telescope.

As this spot group created the greatest magnetic disturbance known in the past forty years, a brief account of its activities may not come amiss.[1] The spot appeared around the eastern limb of the sun on May 8. It was first a single spot with scattered umbrae in a dark penumbra. By May 13, it had separated into two large spots. When the maximum area was attained on May 14, the group covered about 12° in longitude and 6° in latitude, so that a large area of the sun's surface was actively disturbed. Not only was the spot large and active, but it was placed near the solar equator, and since the earth's heliographic latitude was only $-2^\circ.4$ conditions were ripe for a pronounced display on the earth. Minor but well-marked fluctuations of the magnetic needles began on May 11 and 12. A phase of very great activity began on May 13 at $13^h\ 10^m$, G. M. T. A second and more intense phase of the magnetic storm commenced at $16^h\ 8^m$, G. M. T. on May 14, and the speed and amplitude of the needles grew gradually greater on May 15, when the greatest intensity was reached at $7^h\ 30^m$, G. M. T. The protracted magnetic storm had not subsided when the spot, due to the rotation of the sun, moved around the western limb on May 21.

To reach a spot group approximately equal in activity to that of 1921, we must go back in the records to the year 1882, May 11–21. In 1921, the finest display of the aurora and the greatest phase of the magnetic storm were coincident with the passage of the spot group across the sun's meridian. The remarkable feature connected with this group was that the magnetic storm persisted until the spot reached the sun's edge. Consequently, we must either assume that the magnetic display recorded on the earth when the large spot was on the limb of the sun was in reality caused by an invisible spot near the sun's meridian, or we shall have to modify our ideas that the magnetic effects of spots proceed from the sun in approximately radial directions only.

The magnetism possessed by the earth, since it affects so many of the details of our everyday lives, is one of the most

[1] Cortie, *Monthly Notices, R. A. S., 81,* 515, 1921.

important properties of the earth. Does the sun resemble the earth in also being a huge magnet? The appearance of the streamers of the solar corona, especially near the poles, led Bigelow to advance his well-known hypothesis that the sun must be a magnet since the polar streamers of the corona at sun-spot minimum greatly resembled the lines of force proceeding from a magnetized sphere. It seems also reasonable to suppose that the rotation of the enormous sun, carrying, as it does, electrically charged particles on its surface, would create a magnetic field. It is therefore of great importance that observations be made to determine this general magnetic field of the sun. The great success attained by Hale in investigating the magnetism of sun-spots led him to expect similar success on the sun as a whole.

The means of attack differed but little from that taken in the investigations of spots. The photographs were secured by means of the 75-foot spectrograph attached to the 150-foot tower telescope. In front of the slit of the spectrograph is placed a Nicol prism in combination with a "quarter-wave plate" built up of mica strips 2 mm wide, mounted so that the principal sections of successive strips make an angle of 45° with the slit and 90° with each other. If the long axis of the Nicol is placed parallel to the slit, the mica strips will alternately extinguish the red and the violet components, and the photograph will have a dentated appearance, the magnitude of the separation of the components shown on successive strips varying directly with the strength of the field. The general magnetic field of the sun is very weak compared with that manifested in sun-spots, and hence complete separation into doublets of the spectral lines affected is not to be expected. It is evident that in the case of the sun's magnetic field the sign of the displacements should be reversed in passing from the northern to the southern hemisphere on account of the change in polarity. To secure the magnetic field of the sun as free as possible from any local effect of sun-spots, it is obviously necessary to obtain photographs when the sun is entirely free from active spots. Several series of photographs taken under satisfactory conditions have been secured. The

difficulty of measuring these photographs, and of securing these measures free from personal and systematic errors, is patent to anyone who has ever engaged in any astronomical measurements requiring the setting on two close components of a double. Moreover, the size of the quantity to be measured is only 0.001 A. As a matter of fact, van Maanen was the only one of the five Mt. Wilson measurers that engaged in the work whose results had a satisfactory degree of consistency. On account of the difficulties in measuring, lines having an intensity greater than 5 in the solar spectrum and weaker than 0 had to be excluded.

The general summary of the results seems to prove conclusively that a general magnetic field exists in the sun, and that in consequence the sun behaves approximately as a uniformly magnetized sphere, with the magnetic axis only slightly inclined to the solar axis of rotation, and with a polarity corresponding to that of the earth. Forty-six spectral lines were investigated, and of these, 30 lines due to *Fe, Cr, Ni, V* and *Ti* show displacements. The strength of the magnetic field determined for each line showed a correlation between field-strength and line intensity, the stronger fields being connected with lines of smallest intensity. Eclipse spectra reveal the information that the weakest solar lines originate at the lowest depths. Since it was possible to measure, for the determination of the strength of field, lines of a solar intensity 5 or less, it is manifest that lines only in a very shallow layer, less than 450 km in depth, can show the influence of the sun's magnetic field large enough to be detected by the present method of attack. The period of rotation of the sun's magnetic axis was found to be 31.52 days. No explanation can be given for this peculiar value of rotation which differs in such marked degree from the equatorial value derived from sun-spots. In fact, no adequate explanation is yet forthcoming to explain the cause of the sun's magnetism.

Since the Zeeman effects exhibited by spots are large enough to be readily measurable, a daily record is kept at Mt. Wilson giving the intensity and polarity of all spots visible on the sun. For this purpose the triplet at 6173.553 A

is observed. A map of the sun is made and on it the polarity of the spot is marked by V or R, according as the violet or red component is transmitted. The strength of the field is also measured, and is recorded on the map. This record maintained by Hale and Nicholson has enabled them to classify spots as unipolar, bipolar and complex. About sixty percent of all sun-spots are binary groups, the single or multiple members of which are of opposite magnetic polarity. Since the date of the spot minimum of 1913, the magnetic polarity of unipolar spots and of the preceding members of bipolar spots, has been like that of a north-seeking pole, and called positive, in the northern hemisphere of the sun, and of opposite polarity, or negative in the southern hemisphere. There are few exceptions to this rule. However, before 1913, the signs were reversed. Will another reversal happen again at the next minimum?

The photographs of flocculi taken with the $H\alpha$ light have shown whirls in the solar vortices taking place outside the region of the spots. Since the visibility of the spot depends on the amount of cooling produced by the expansion of the gases in the vortex, it may happen that even before a spot is displayed, and also after it has disappeared, the local whirls may still exist in sufficient strength to cause a magnetic field. Thus it has been possible to discover what Hale calls " invisible sun-spots."

If the charged particles whirling in a sun-spot vortex are preponderatingly positive or negative, an electric field should be present which should be manifested by the Stark effect. The observations at Mt. Wilson carried out by Hale show no evidence of this effect. The fact that the majority of the enhanced lines in sun-spot spectra are weakened, while none are strengthened, shows that ionization is much less complete in spots than in the general atmosphere of the reversing layer. As a result of Saha's interesting theory, this must signify that no electric field can exist in sun-spots sufficiently intense to overcome the reduction in ionization caused by the diminished temperature of sun-spots.

Of the very greatest interest is the comparison of the re-

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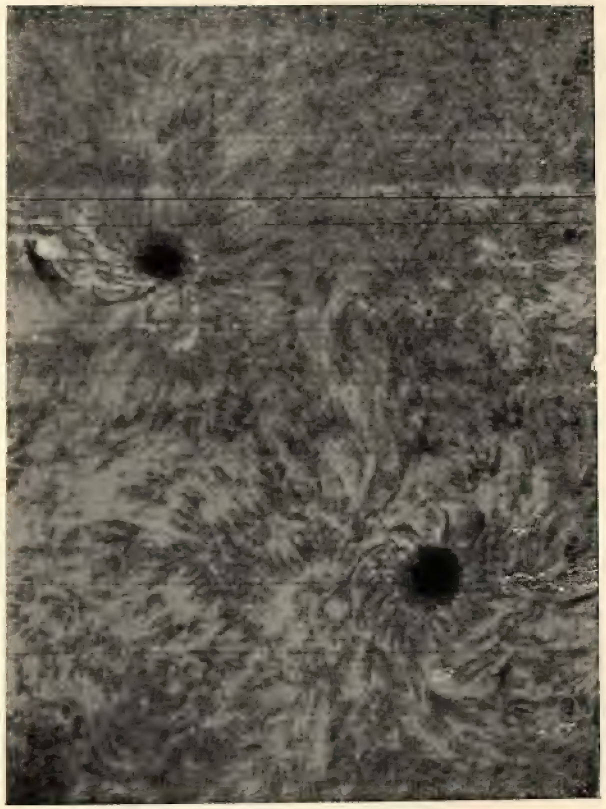


SUN-SPOTS AND HYDROGEN FLOCCULI SHOWING RIGHT- AND LEFT-HANDED VORTICES

Photographed at the Mt. Wilson Observatory, September 9, 1908.

sults of the flash spectrum taken at the time of a total eclipse with those obtained without an eclipse. At Mt. Wilson, Hale and Adams secured successful photographs with the 60-foot tower telescope and powerful spectograph attached. The method employed was to allow light from the sun's limb to fall upon a diagonal prism so placed as to reflect the light horizontally to a second prism immediately above the slit. The first prism was mounted upon a slide with a screw adjustment allowing motion toward or away from the second prism.

After the sun's image has been brought to the slit, the observer selects a bright line of the chromospheric spectrum and brings it into the field of view of an eye-piece, mounted in an opening near the end of the plate-holder. During the exposure, this line is maintained at maximum brightness by guiding with the screw controlling the position of the first diagonal prism, thus moving the sun's image slightly on the slit. The second order spectrum was employed giving a dispersion of 1 mm = 0.9 angstroms; and exposures of four minutes were required in the yellow part of the spectrum, and double this amount in the red.

Two reports on the wave-lengths, etc., obtained from the spectra have been published from Mt. Wilson. The first one by Hale and Adams appeared in *Communications* No. 41, and the second by Adams and Burwell in *Communications* No. 95, the former coming before and the latter after the publication by Mitchell of his flash spectrum results obtained at the eclipse of 1905. For obvious reasons, the second communication from Mt. Wilson is more complete than the first. Unquestionably the photographs at Mt. Wilson were secured at a very low level, but whether at a lower level than the 1905 eclipse spectra it is rather difficult to decide. In comparing the results obtained within and without an eclipse, there are very great advantages in favor of the latter method, the most important being the possibility of securing a much higher dispersion by the method without an eclipse than can be secured at the time of an eclipse. The dispersion of the 1905 eclipse spectra was 1 mm = 10.8 angstroms, or one-twelfth of that in the discussion in the *Mt.*

Wilson Communications. On account of the shortness of the exposures available at eclipses, one cannot attempt to employ a much larger dispersion than that which comes from a concave-grating of ten-foot focus and of 15,000 lines per inch when the grating is used objectively without slit. Because the exposures without an eclipse can be increased at will, the dispersion can also be increased, and it is quite possible for the Mt. Wilson observers to employ the 150-foot tower telescope with the 75-foot spectograph in the second order and thus secure a dispersion thirty times that of the 1905 eclipse spectra. At an eclipse only two exposures of the flash spectrum are possible, and unfortunately the best focus is secured more or less only as the result of a happy accident. Outside of an eclipse there are no such limitations, observations may be repeated until moments of good seeing are secured and until photographs are obtained of the best definition exhibiting the results of layers sufficiently close to the sun.

The comparison of the results obtained with and without an eclipse may be briefly summarized here. First, let us take up the *number* of the lines photographed by the two methods in a given region of the spectrum. Compared with spectra taken outside of an eclipse those obtained at an eclipse have the two-fold disadvantage of the much smaller dispersion and of the superposition of the eclipse lines on a very strong continuous spectrum. In the process of measuring the eclipse spectra, it was difficult to differentiate the weakest lines from the continuous spectrum. Consequently many eclipse lines were actually measured in the flash spectrum but were not published at the time (*see Astrophysical Journal, 38,* 481, 1913), for it seemed unwise to add any lines to the publication unless those lines could be definitely identified with lines appearing in Rowland's tables. For these reasons, therefore, it must be concluded that the number of the *weakest* lines secured at Mt. Wilson without an eclipse is probably not greater than the number found on Mitchell's eclipse spectra. Since the intensities of the lines depend on the levels at which the lines originate, it seems highly probable therefore, that the levels photographed within and without an eclipse are not very different. For the stronger lines originating at higher levels, the intensities inside and outside of the eclipse greatly differ, such variations however being readily explained on account of these very differences in level.

Regarding the accuracy of the wave-lengths, the following may be said. On account of the spreading of the photographic images of the strong lines of the eclipse spectra it is impossible to secure accurate wave-lengths from such lines. Omitting these lines, the eclipse wave-lengths differ from Rowland on the average by 0.020 angstroms. With the twelve-fold greater dispersion at Mt. Wilson the wave-lengths have an accuracy of 0.012 angstroms,[1] being a precision about twice that obtained from eclipse spectra.

With a slit tangent to the sun's limb it is evident that the *length* of the lines in the spectrum taken without an eclipse should furnish information regarding the levels at which such lines originate. Such measures have not as yet been carried out at Mt. Wilson. The need of more reliable determinations of the levels at which the spectrum lines of different intensities originate and the great importance of such knowledge in present-day problems of solar physics cannot be over-emphasized.

As already has been stated, the spectroscopic method of determining the solar rotation has greatly widened our knowledge by showing the law of equatorial acceleration (or polar retardation) in heliographic latitudes where no spots exist, the law of rotation being similar to that determined from observations of spots alone. The law underlying the solar rotation is now known with much greater accuracy than could have been possible from sun-spot observations alone since the spots are subject to peculiar motions of their own. Unfortunately, the spectroscope measurements seem to be subject to large systematic errors, the causes for which could not have been foreseen when the research was started. In view of the fact that the energies of so many observers have been spent in this work which has now been carried on for a number of years, it might be

[1] *Mt. Wilson Contributions,* No. 95.

well to stop, and ask what scientific results in addition to those outlined above, have been obtained. It has been shown that vapors at different levels rotate at different speeds and that the greater the elevation the greater the angular speed. The red line of hydrogen rotates at a higher velocity than the gases forming the average of the reversing layer and likewise exhibits less polar retardation. In spite of the fact that the discussion of the measures appears to confirm the conclusion that at spot maximum the sun rotates faster than at spot minimum, further researches seem to show that the differences between maximum and minimum is not real but is due to the presence of systematic errors in the measures. Moreover, eight years of careful work at Mt. Wilson has not revealed any change in the rotation that can be detected, and accordingly, it seems highly probable that any variations in rotational speed are so small in size that they cannot be measured by any methods at present (1923) in vogue.

The recommendation is therefore made to the investigators of solar rotation, and is hereby urged upon them for their consideration, that they curtail their work on solar rotation and instead devote their energies for a short while to the flash spectrum without an eclipse. With the equipment already in hand, and under good conditions of seeing and with adequate facilities for proper guiding, good photographs of the flash spectrum should be possible at very low levels. The accurate measurement of wave-lengths, and particularly the determinations of the levels at which different lines of the spectrum originate, will add greatly to our knowledge concerning these lines and will supply information so sadly needed in deciphering the laws underlying the production of spectral lines. The Bohr atom and Saha's theory of ionization have made possible the identification of new spectral lines in the sun and in the laboratory, and undoubtedly we are on the eve of a very great advance in knowledge regarding the laws underlying the production of lines in the spectra of various sources.

CHAPTER XVI

THE STRUCTURE OF THE ATOM

DURING the past two and a half centuries, the astronomer and the mathematician have worked in close cooperation investigating the distances and motions of the bodies forming the sidereal universe. Under the magic wand of their combined labors, the complexity of the Ptolemaic system has given way to great simplicity and beautiful order, revealing motions obeying the inverse square law of Newton, or the very slight modification of this law of gravitation demanded by the theory of relativity. During the progress of these investigations, our conceptions of distances and dimensions have been gradually modified, till now, from the work of Shapley and others, we are made aware that the sidereal universe has a radius which may even exceed 10^{21} meters or one hundred thousand light-years.

While the astronomer has thus been reaching out to greater and yet still greater distances in the direction toward the infinite, the physicist and the chemist, on the other hand, have found solar and planetary systems of nearly infinitesimal dimensions within the realm of the chemical atom. The radius of the electron we seem to think we know is equal to 1.9×10^{-15} meters. It has been tacitly assumed that the planetary motions within the atom obey the gravitational law. The investigations of the physicist have been hampered by the failure of the mathematical astronomer to solve the general problem of the motions of *n* bodies. Fortunately, however, experimental evidence has not depended exclusively upon mathematical analysis.

The amazing development of our conception of the atom has come within the past two and a half decades, the beginning taking place with the study of streams of negative corpuscles or electrons. On its discovery, radium seemed

superficially to exhibit a contradiction of the laws of conservation of energy. Heat and light were spontaneously emitted without any apparent changes in the radium, and thus a continuous supply of energy seemed evolved which set at naught that fundamental law of physics. But it was soon found that with the giving off of energy in radiation, the radium itself did utterly change and here the philosopher's stone seemed at last to have been discovered, for it was found that one chemical element actually changed into another.

And to think that after all the whole science of radioactivity was more or less the result of a happy accident! The year following the discovery of X-rays in 1895 by Röntgen, Becquerel of Paris wished to test the phosphorescent action of certain substances by wrapping a photographic plate in black paper, and placing on it the substance to be examined, which was then exposed to sunlight. By good fortune a preparation of uranium was chosen and the photographic plate was darkened. The Becquerel rays were thus discovered, and it was soon found that, like the X-rays, these rays penetrate substances impervious to light, even passing through thin plates of metal. The experiments were always made by placing the phosphorescent substance in the sunlight on top of the black paper enclosing the photographic plate. But one day the sun was clouded, and the plate and the phosphorescent substance were placed away in a desk and were left there for several weeks. Becquerel for some reason developed the plate, and was surprised to find the plate darkened as before, thereby showing that probably neither sunlight nor phosphorescence had anything to do with the action on the photographic plate. Thus was born, in 1896, the new science of radioactivity!

Besides the effect on the photographic plate, radioactive substances manifest themselves in three different manners: first, by exciting phosphorescence and fluorescence; second, by causing the air near them to become conductors of electricity; but most startling of all, by the continuous generation of light and heat.

Mme. Curie recognized that radioactivity was a property

of the atom and starting with this in view she found that the residues from the mine at Joachimstal, Austria, were three to five times more radioactive than uranium. From this residue she separated out a new substance, far more active than uranium which she called polonium, in honor of the place of her birth. Later she discovered radium. This appears to be an element with atomic weight 226, and it is found in excessively minute quantities, there being only one part in five million of the best pitchblende. In 1899, Rutherford showed that the radiation from uranium was complex, consisting of (1) the α rays, which are absorbed by a sheet of paper or a few centimeters of air, (2) of a hundred-fold more penetrating β rays, capable of passing through several millimeters of aluminium, and (3) of still more penetrating γ rays capable of passing through quite a thickness of iron and lead. The β rays are deflected by a magnetic field. Becquerel and Kaufmann showed that the β rays were negatively charged particles projected with a velocity approaching that of light. The very penetrating γ rays are not deflected in a magnetic or electric field, and are probably closely connected with X-rays.

Though the α rays are the least penetrating, they are much the most important of the three types of radiation. They are deflected much less by a powerful magnetic field than the β rays, and in the opposite direction, showing that the α rays consist of a stream of positively charged particles. Alpha rays, therefore, will affect a gold leaf electroscope, and this old instrument gives one of the most sensitive methods of measuring the amount of radiation. In fact, Rutherford has shown that it is not difficult to measure with certainty the presence of radium in a body which contains as small a quantity as 10^{-11} grams of radium!

The maximum velocity of the α rays is 12,000 miles per second. These α rays thus move with velocities hundreds of times greater than the fastest moving meteor. Everyone is aware of the enormous energy possessed by a meteor moving, say, at 40 miles per second. But energy varies as the square of the velocity, and thus the α particle of radium possesses a quarter of a million times more energy, mass

for mass, than a swiftly moving meteor. In this enormous energy of the rays lies the secret of the surprises of radium. From whence comes this enormous store of energy?

In addition to its power of sending out radiations, radium possesses another important property, shared in by the radioactive substances actinium and thorium, namely that of continuously emitting a radioactive " emanation " or gas. This property is rendered very striking if a specimen of radium bromide is dissolved in water and the liquid evaporated down to dryness again to get the solid substance. This simple process has caused the radium to lose the greater part of its radiation. Strangely enough the radium slowly regains its activity, and if left entirely to itself, at the end of a month it is as radioactive as ever. Rutherford has showed that the solution in water causes the radium to give off a gas called " radium emanation." This emanation has all the properties of a true gas, it can be liquefied at a temperature of $-150°$ C, but it is 100,000 times more radioactive weight for weight than radium. It does not combine with any known substance, and is not acted upon by any chemical reagent. It is not a radium compound, but it is a new element with an atomic weight which appears to be 222. It takes its place along with the rare gases of the air, argon, helium, neon, etc., and it gives a characteristic bright-line spectrum which shows neither the radium nor helium lines. It seems, therefore, that the element radium has been transformed into another element, radium emanation, or niton. If after a month, the radium is again dissolved in water and evaporated to dryness as before, the radium loses its activity, and a fresh crop of emanation is produced. This same process may be repeated as often as possible with the result always the same, and we are perforce compelled to assume that the radium is continually manufacturing emanation, continually changing itself into a new element. This is really only the first of a series of changes, for radium emanation changes into radium A, and this in turn to radium B, and so on. This change is an atomic change going on within the atom. But how does this change progress?

When the radium has given off the emanation, it still gives out α particles, but only about one-fourth as copiously as before the radium was put in water. The α particles are produced by the same change as makes the emanation, and the radium atom is therefore divided into emanation and α particle.

Observations of the velocity and mass of the α particle made by Rutherford indicate either that the mass of the α particle is twice that of the hydrogen atom, or if the charge carried by the α particle is twice that of the hydrogen atom, then the mass of the α particle is four times that of the hydrogen atom and must therefore be an atom of helium. Hence each atom of radium apparently breaks up into one atom of helium and one of radium emanation.

All that was necessary to complete Rutherford's proof that helium was actually given off from radium, was to show experimentally that helium was thus produced. This was accomplished in 1903 by Sir William Ramsay and Frederick Soddy. A tube was filled with radium emanation which was separated from all other gases by condensing it with liquid air and removing by a pump the gas not condensed. This spectrum tube was sealed and the spectrum of the gas could be examined at will. At first no helium lines were visible, but after a lapse of three or four days, when the radium emanation had disintegrated, the spectrum of helium gradually made its appearance, and finally the whole helium spectrum was complete. Similarly, Debierne has found by the spectroscope that helium is produced from the radioactive substance actinium, and Soddy has produced helium from uranium and thorium. Helium, therefore, has been found experimentally to be produced by the radioactive substances radium, thorium, uranium and actinium. These substances are alike in that each emits α particles. Hence, α particles are atoms of helium. Rutherford and Royds, however, have given a still more conclusive proof that the α particle is an atom of helium. These α particles are capable of penetrating a certain small but definite thickness of glass. Glass may be blown very thin but yet retain its ability to remain air tight. Radium emanation was stored in such a thin-walled vessel and this enclosed in a second

vessel. Alpha particles given off from the radium emanation thus could penetrate through the very thin glass walls, but were stopped in the outer vessel and were there collected. At first the gas in the outer vessel was found to contain no helium, but after some days, helium lines appeared in the spectrum, proving beyond a question of doubt that radium gives off helium.

It is even possible to measure the rate of growth of the helium, which measures show that in a year, 168 cubic millimeters of helium are spontaneously manufactured by each gram of radium. Rutherford and Geiger in this connection achieved one of the greatest triumphs for experimental science in being able to count the number of helium molecules or atoms that are ejected per second from one gram of radium. Indeed two different methods were devised which led to the same results. Both methods depend on the fact that each atom of helium as it is ejected gives a small flash like a meteor. By an electrical method, these flashes were counted by Rutherford and Geiger and it was found by them that thirty-four thousand million (3.4×10^{10}) atoms of helium are ejected every second from each gram of radium. This number is in exact agreement with that obtained by noting with a microscope the number of scintillations on a given area in a given time by the spinthariscope, invented by Sir William Crookes. Thus at the same time there was measured the amount of helium produced from radium, and likewise was given the number of molecules present in matter, information which was needed to complete many theories in physics.

Investigations in radioactivity accordingly have given an entirely new conception of the atom. The atom is no longer one and indivisible, but certain atoms at least are transformed into other atoms, each radium atom being changed into one atom of helium and one of radium emanation. These atoms are continually changing, no less than thirty-four thousand million atoms of helium being produced each second of time from each gram of radium. As the atoms disintegrate, enormous stores of energy are let loose, and this energy manifests itself as light and heat. The heating

effect of this energy has been measured and has been found to be 118 gram-calories per hour per gram of radium. A specimen of a grain of radium bromide would evolve about four calories per hour. In four years about 140,000 calories would have been evolved. An equal weight of coal would during complete combustion give out about 500 calories. Hence, the radium in four years would give 280 times as much heat as if it had been coal and had been completely burned, and yet the radium in this time would diminish so very little in weight that it would be absolutely impossible to detect this diminution by the most sensitive balance known to modern science. The energy of radium comes from the disintegration of its atoms. A quantity of radium would take 1760 years to disintegrate, so that in the complete life of one grain of radium about 100,000,000 calories are set free. This is 200,000 times more energy than if it were pure coal and entirely burned!

Helium being permanent and not transitory, must accumulate as the result of radioactive changes. In these changes, Soddy has shown the remarkable sensitiveness of the spectroscope in detecting slight quantities of helium for he has proved, in numerous special experiments, that the D_3 line of the helium spectrum can be detected with certainty, if only one millionth of a cubic centimeter, or one five-thousand-millionth part of a gram of helium is present.

An achievement of far-reaching importance in all theories of physics was the discovery by Sir J. J. Thomson of a body having a mass much less than that of the lightest known atom, hydrogen. This body, called by its discoverer a corpuscle, but now known as an electron, is 1/1845 part of the mass of the hydrogen atom. A further study of the electron showed that it is always associated with a negative charge of electricity and in fact carries a unit charge of negative electricity. The physicist has now become convinced that the atom is an electrical structure made up of nearly equal amounts of positive and negative electrical charges. The atom is believed to consist of a central group of elementary positive charges, or protons, with a smaller number of negative charges, or electrons, called the nucleus,

and about this nucleus there is an outer system of negative electrons, varying in number from one to ninety-two. These outer electrons can be expelled from the atom by a number of different methods, such as the application of heat, impact of ions, exposure to ultra-violet or X-rays, or they may be emitted by radioactive substances; in fact, the β rays consist of a stream of negatively charged particles.

The discovery by C. T. R. Wilson that the charged ions produced in gases by α and β rays become the centers for the condensation of water vapor paved the way to experimental work of a remarkable nature. Millikan has secured extraordinary results by utilizing tiny drops of oil in place of water, and as a result of his experiments, he has been able to prove conclusively that the electrical charges carried on ions "all have the same value or else small exact multiples of that value." This fundamental unit is the same, both for positive and negative electricity and is numerically equal to the charge carried by the negative electron. This unit charge of electricity was measured by him to an accuracy of one part in 1000. With this information, it was possible to estimate with greater accuracy the mass of the electron in grams and the number of molecules of any gas per cubic centimeter at 0° C and 760 mm. pressure.

Since we know therefore the size of a molecule and the number of molecules per cubic centimeter, it is possible to compute the number of molecules through which the α or the β rays emitted by radium must pass in going a given distance. The extraordinary fact revealed (by the photographs of Wilson, referred to above) is that the swift-moving β particles pass, on the average, through as many as 10,000 atoms before coming close enough to an electron to detach it from its system and form an ion. In fact, it has been shown by Eddington[1] that when an electron encounters an ionized atom it will be captured if, and only if, it actually hits the nucleus of the atom. The electron must therefore form but a very minute portion of the space enclosed within the atomic system. The α particle being an atom of helium with a mass more than seven thousand times that of the negative

[1] *Monthly Notices, R. A. S., 83*, 32, 1922.

electron, it cannot be deflected from its course by an electron which is of very minute mass, but only by some ponderable mass at least comparable with that of the helium atom. This heavier mass is found at the nucleus of the atom. As a result of Geiger and Marsden's experiments on the scattering of α rays, it was found that when these rays passed through very thin metallic foils, the deflections witnessed could be explained only by assuming a very close approach to a small but massive charge particle. Rutherford[1] was accordingly led to assume that the typical model of an atom consisted of an exceedingly minute and comparatively massive positively charged nucleus, about which is collected a number of electrons. Each and every one of the electrons forming the outermost parts of all atoms are exactly alike and each carries a unit amount of negative electricity. Since each atom is electrically neutral, the charge on the positive nucleus must be equivalent to the sum of those carried on the N electrons. The value of N for each of the atoms is a fundamental constant, for cn it depends the size of the electric field surrounding the nucleus and the peculiar arrangement of the external electrons, which in turn determine the physical and chemical properties of the atom. Experiments in 1911, by Barkla on the scattering of X-rays indicated that the number, N, of electrons in an atom was approximately half the atomic weight of the element. This conclusion was abundantly verified by the magnificent work of Moseley. He found that the X-ray spectrum was similar for all elements, and that when he plotted the square root of the frequencies of the characteristic X-ray spectra, all the elements examined arranged themselves upon nearly perfect straight lines. The atoms were then numbered in the order in which these spectra placed them to give these straight lines.

The ordinal number corresponding to the place occupied by each element in the periodic table (p. 236) has been termed its atomic number. The work of Moseley showed that all the chemical elements took their proper places in the periodic table, and as uranium is the heaviest atom

[1] *Phil. Mag., 21*, 669, 1911, and *27*, 488, 1914.

known (atomic number 92) there can only be 92 species of elements. In the periodic table there are but five missing elements, with numbers 43, 61, 75, 85 and 87.

These discoveries of the physicist have been the greatest boon to the work of the chemist. The latter has always had great faith in the principles underlying the Mendeléeff table, but in this table, arranged in order of increasing atomic *weights,* certain discrepancies appeared; for instance, argon of atomic weight 39.88, from its properties was compelled to find a place in the table before potassium having a smaller atomic weight of 39.1. The system of atomic numbers places *A* with number 18, in its rightful place before *K* with atomic number 19. In a similar way, the system of atomic numbers places *Co* in the table before *Ni,* instead of after it, if arranged according to atomic weights.

With a knowledge of atomic numbers, the difficulties of classification presented by radioactive substances were now cleared away. Soddy has shown that when an α particle is emitted, the position of the element in the periodic table is shifted by two numbers to the left towards smaller numbers, while if a β particle is emitted the atomic number increases by one unit, and the place is shifted one to the right. Since the α particle is an atom of helium with positive charge 2 and mass 4, while the β particle is a negative electron with no appreciable mass, it is evident that the emission of an α particle will diminish the atomic weight by 4, but the emission of a β particle will cause no change in the atomic weight. Consequently, if the emission of an α particle by a substance is followed by two successive changes in which β rays are set free, the net result will be that the element, after experiencing these three changes, will move back again into the position in the periodic table it had held originally. These changes have not altered the size of the atomic number, but have diminished the atomic weight by 4, and consequently, it is possible for two or more elements to have the same atomic number but differ in their atomic weights. Such elements are known as *isotopes.* Isotopes are indistinguishable from each other by any chemical tests, or by any spectroscopic tests since the spectra are identical. Radium (at. wt. 226), *Th X* (at. wt. 224) and *Ac X* (at. wt. 222) are examples of isotopes, each possessing a nuclear charge or an atomic number of 88.

Since all masses are nothing more than electromagnetic manifestations, and since the mass of the electron is very minute and negligible compared with the mass of the nucleus, it should be possible to compare the masses of different elements by subjecting them to successive electric and magnetic fields. This method of "positive ray analysis" developed by J. J. Thomson consists in measuring the ratio of charge to mass. This was made possible by a beautiful photographic method, which in the capable hands of Aston has greatly improved our knowledge regarding the atoms. Although demanding technical skill of a very high order, the chemical examinations can be carried on by simple methods leading to definite results. A small supply only of the gas to be investigated is required, it need not be chemically pure nor need any special care be taken to wash away from the vacuum tube all traces of the last gas investigated. According to Aston, it is impossible to remove from a tube "all visible traces of a misspent career." The experimental measurements show that the elements whose atomic weights are whole numbers, with oxygen assumed as 16.00, are *pure* elements. Such elements are *He, C, N, O, F, Na, P,* and *S.* All other elements with fractional atomic weights are *mixtures* of isotopes, each of the isotopes however having a whole number for its atomic weight. *B* (at. wt. 10.9) is a mixture of two isotopes of masses 11 and 10; *Ne* (at. wt. 20.2) consists of two isotopes, masses 20 and 22; *Mg* (at. wt. 24.32) is a mixture of three, of masses 24, 25 and 26; *Cl* (35.46) consists of two masses 35 and 37; while *Xe* and *Hg* are each made up of no less than 6 isotopes.

These results suggest the view that the nuclei of all atoms are made up of multiples of hydrogen nuclei each carrying unit positive charge, the combination being bound together by the external electrons. We therefore are brought back to a hypothesis of Prout propounded as long ago as 1815. We thus see that practically the entire mass of the atom is confined to the nucleus, but the size of the nucleus is very

minute compared with the whole volume of the atom. In fact, the radius of an electron cannot be larger in comparison with the radius of the atom than is the radius of the earth compared with the distance from earth to sun. Each atom therefore forms a miniature solar system, the external electrons being held in place and compelled to perform their orbital motions by the comparatively massive nucleus. Since there may be as many as 92 external electrons, it is evident that modern mathematics cannot furnish a general solution of the motions of the electrons, except in the case of the very simplest of the atoms.

Since the chemical and physical properties depend on the distribution of the electrons of the outer atom, there have been many attempts to formulate a structure for the atom. From such attempts have gradually evolved atomic models of two different types. The Lewis-Langmuir atom has been very successful in explaining the chemical properties, particularly the valence. This atom is not based on any dynamic principles. Valence, which measures the power to combine, may be positive or negative depending on whether the atomic system has too many or too few electrons to make a stable combination. The inert gases — helium, neon, argon, krypton, xenon and niton — are elements which have no power to form compounds. Such atomic systems under ordinary conditions cannot capture an electron from another atom, nor can they get rid of one of their own. The inert gases have atomic numbers of 2, 10, 18, 36, 54 and 86, and hence we may imagine the atoms as if made up of concentric shells of electrons, the shells containing 2, 8, 8, 18, 18 and 32 electrons respectively.

Except for the hydrogen system, all atomic structures have the two electrons forming the system of helium as their innermost shell. Since helium is inert and cannot take up another electron, the third electron which forms lithium must be a single electron in a shell exterior to the helium system. The lithium system is therefore not very stable, and readily gives up its external electron. It has a positive valence of one. The system of fluorine, with seven electrons in the second shell, may be regarded as being in a position

readily to capture an electron from an atom in its neighborhood, and so it has a positive valence of seven or negative valence of one. Likewise oxygen may be regarded as having positive or negative valences of 6 and 2 respectively. The Lewis-Langmuir atom is very successful in explaining the relative positions of the elements in the periodic table. The electrons forming the atom of this model are relatively fixed in position, for though each electron may be in motion, it is confined to a small portion of the space occupied by the atom. Our conceptions of this atomic model are no doubt in a transitional stage.

Great difficulties, however, appear when discussing atomic models on the principles of physics, especially when there is a transference of energy from place to place, or when the motions of the atoms make them depart from the steady state thereby causing emission or absorption of light. After repeated failures to explain these matters by means of the accepted theories, Planck made one of the most startling proposals ever presented to the scientific world, from which developed his celebrated *quantum theory*. According to Planck, it was assumed that the transference of energy can only take place in definite but very small units, and that the total energy transferred is always an integral multiple of this small unit, called the energy quantum. This can be expressed simply in mathematical terms. If E_1 and E_2 represent the energy of a system before and after radiation has taken place, then the energy spent in radiation is $E_1 - E_2 = h\nu$, where h is Planck's constant and ν is the frequency of vibration of the body concerned. This mathematical equation gives expression to the simple statement that the total amount of energy emitted or absorbed by a radiating body is always proportional to the frequency of vibration, which in turn is inversely proportional to the wave-length of the light emitted or absorbed.

The very radical nature of Planck's hypothesis may be estimated when it is stated that it stands at variance with all the previously known laws of mechanics developed to explain the motions of material objects of large dimensions. As a matter of fact, there is no absolute necessity that the

same laws that apply to ponderable material in a gross state must also be applicable to simple atoms, unless these atoms are in their steady states not radiating energy. This contradiction has given rise to the expression " classical dynamics " which explains the motions of matter in obedience to the law of gravitation. One fundamental conclusion of the quantum theory is that motion is not the continuous process that we have accustomed ourselves all our lives to believe; but the motion takes place " steadily by jerks," the jerks however being so small that the process is to all practical purposes continuous.

The only atom so far proposed, which is at all successful in explaining the physical facts, and more particularly the spectroscopic data, is the Bohr-Sommerfeld atom. This was first proposed in 1913 by Bohr, following an attempt by Nicholson to account for spectrum lines in the solar corona (*see* Chapter XVIII), and it is based on Planck's quantum theory of energy. In explaining the motions of the external electrons, little hope can therefore be expected from the classical dynamics, for this would require the solution of the problem of n bodies when n is large. For the present, assumptions must be made for the purpose of securing results, and in spite of much inconsistency, the quantum theory of spectra is the only satisfactory attempt so far made toward interpreting spectral series. In the simple case of the hydrogen atom and ionized helium, each with one external electron, the Bohr-Sommerfeld method has been very successful in reproducing many of the details of the spectra both in electric and magnetic fields. On the basis of this theory, the problem of atomic structure consists in building up each atom in such a way that the passage of an electron from one stationary state to another will give wave-lengths and frequencies in agreement with those observed by spectrum analysis.

In the investigations of spectra, the first of the lines to show an arrangement in series were those due to hydrogen, discovered in 1880 by Huggins in the spectra of white stars. This series is an extension of the four lines visible in the solar spectrum. A new era in spectroscopy started in 1885

when the law underlying the hydrogen series was discovered by Balmer. The thirty-five lines found in the flash spectrum are represented by the formula

$$\lambda = 3646.125 \frac{m^2}{m^2 - 4}$$

where λ is the wave-length on Rowland's scale and m takes the values 3, 4, 5. . . .

Shortly afterwards, Kayser and Runge, and Rydberg independently, began the publication of their splendid researches. Rydberg's investigations are of the greatest importance since they have laid the foundation for all future work on spectra in series. He began by sorting out doublets and triplets and thus ascertaining the lines which belong together in a series. He was able to distinguish three chief kinds of series, as:

Principal, including the strongest lines
Diffuse, of intermediate intensity
Sharp, including the weakest lines.

Each of these three series may consist of single, double or triple lines. Each and every series always converges towards a limit at short wave-lengths, and the lines at the same time diminish in intensity. A fourth so-called " fundamental " series with lines mainly in the infra-red has been discovered by Bergmann.

Many and varied are the mathematical formulae employed to represent the series of spectra. The most satisfactory formula, which is due to Rydberg, takes the following form:

$$\nu_m = A - \frac{N}{(m + \mu)^2}$$

where A is the limit of the series, N is the " Rydberg constant " for hydrogen, and the wave numbers ν_m are obtained by assigning successive integral values to m. μ may be regarded as a decimal part to m, though it is sometimes greater than unity. For the details of the investigations of

series spectra, one would do well to read Fowler's excellent *Report on Series in Line Spectra,* 1922.

Of special interest in dealing with the flash spectrum are the investigations regarding enhanced lines. Fowler has shown[1] that these lines form series entirely similar to those of the ordinary lines. The formula representing the enhanced series, however, differs from that of the ordinary series in that the Rydberg constant N is multiplied by 4. This has a simple explanation from Bohr's theory. The ordinary series lines are emitted when an electron of charge e returns to an atom from which it has been displaced. The enhanced lines, on the other hand, are produced when an electron returns to the atom which has already lost another electron through ionization; consequently, two electrons are detached from the atom, each electron carrying a charge e, or a total charge $2e$. The formula for the Rydberg constant N, involves the square of the charge e, and hence for the enhanced lines the multiple 4 appears. Enhanced lines therefore belong to the ionized atom, or one which has lost a negative electron and hence carries an excess of positive charge. According to a suggestion by Saunders, $He+$, and $Ca+$, refer to ionized helium and calcium, the addition of the $+$ sign following the chemical symbol signifying that the atom is not electrically neutral but carries a $+$ charge. After an atom has lost one electron and thus becomes ionized, it may lose a second electron and become "doubly ionized." The symbol adopted for calcium under these conditions is $Ca++$, the atom carrying two extra positive charges. According to Bohr's theory, the charge concerned in the production of spectrum lines by such an atom is $3e$, and hence the Rydberg constant N must be multiplied by 9.

This is not the place to give the mathematical theories underlying the formation of spectrum lines, but a synopsis may be given of the more important developments found in Fowler's *Report on Series in Line Spectra,* 1922, and in Foote and Mohler's *The Origin of Spectra,* 1922. Any theory must explain why the frequency of any line in a spectrum appears always as the difference between the terms

[1] *Phil. Trans.* A. *214*, 225, 1914.

of a quantity, neither of which represents a spectral line, and must furnish an explanation of the physical meaning of the two terms, and must further explain how an emitted frequency comes to be the difference of two of these.

Adopting the idea of Rutherford, outlined above, that each atom consisted of a heavy nucleus carrying a positive charge which was surrounded by negative electrons, Bohr was able to give a satisfactory theory in the case of the simplest type of atom. The hydrogen atom is such a unit since it consists of a single electron in orbital motion around the nucleus, and equally simple are the atoms of enhanced helium and doubly enhanced lithium. According to the Bohr theory, the single external electron is free to traverse certain specified orbits, which are determined in the simple case of circular orbits by the condition that the angular momentum is an integral multiple of $h/2\pi$, where h is Planck's constant, derived from the quantum theory. When the motion of the electron is confined to one of these stationary orbits, there is no radiation. Emission occurs only when the electron passes from one stationary orbit to another. Without attempting to explain the mechanism which causes the electron to pass from orbit to orbit, Bohr supposes that the transition is followed by the emission of light, the frequency of which can be determined from the quantum theory. In fact, the energy radiated is equal to the differences of the energies of the electron in the two orbits concerned, and is assumed to be one quantum of energy, $h\nu$, where h is again the Planck constant and ν is the frequency. At a given instant, any one electron falling from an external to an internal orbit causes one line only in the spectrum, and it is the summation of the actions of a large number of electrons that causes the whole series of spectrum lines.

By the elementary laws of mechanics, it is possible to derive the necessary equations for orbital motion. Taking E and M as the charge and mass of the nucleus, e and m as the charge and mass of the electron, c the velocity of light, and $\nu = n/c$, the wave-numbers of the lines, then for the case of hydrogen

$$\nu = \frac{2\pi^2 E^2 e^2}{ch^3} m \left(\frac{1}{t_1^2} - \frac{1}{t_2^2}\right)$$

where t_1 and t_2 are integers.

This formula is of exactly the same form as that which represents the Balmer series of hydrogen, the quantity outside the brackets representing the Rydberg constant. In fact, as a splendid confirmation of Bohr's theory, the Rydberg constant, N, calculated from Millikan's data, furnishes a value which agrees with that found from spectral series within an accuracy of one part in 1000.

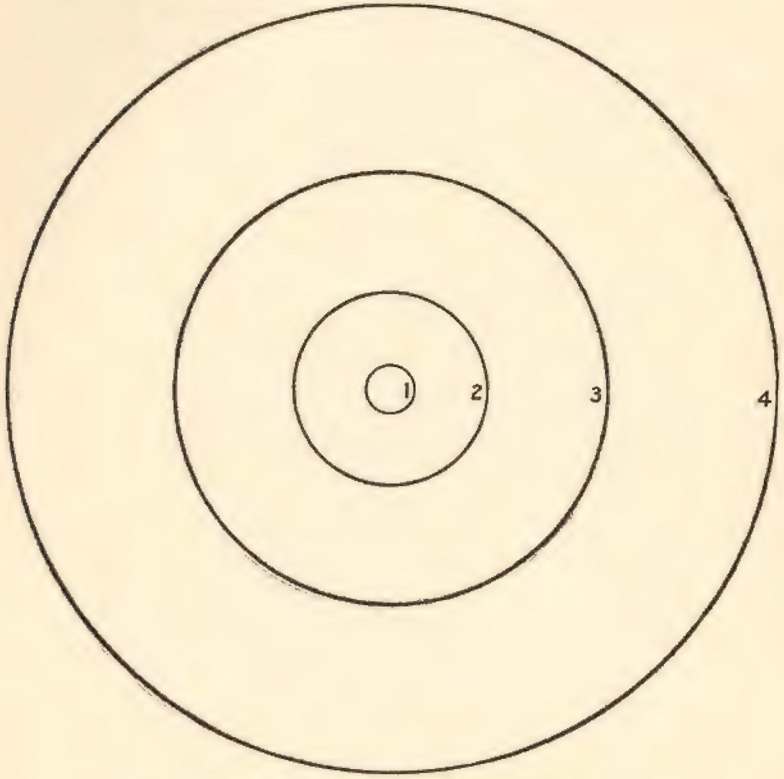


FIG. 4 Orbits of the hydrogen atom.

The successive orbits of hydrogen are in the ratios 1^2, 2^2, 3^2. . . . In the normal state of the atom the single electron

revolves in the innermost orbit. When the atom is disturbed by an electrical charge so that the electron is removed to a great distance from the nucleus, the electron will successively occupy different orbits on its return to its neutral position. The first line of the Balmer series, $H\alpha$, corresponds to the fall of the electron from orbit 3 to orbit 2, the second line, $H\beta$, to the fall from orbit 4 to orbit 2, and the following lines to the fall from orbits 5, 6, 7, . . . in each case to orbit 2. In the formula above, the Balmer series is represented by making $t_1 = 2$, and $t_2 = 3, 4, 5. . . .$ The series discovered by Theodore Lyman of Harvard in the Schumann region in the extreme ultra-violet corresponds to falls of the electron from orbits 2, 3, 4 . . . to the innermost orbit 1, while the lines in the infra-red series are caused by falls from orbits 4, 5, . . . to orbit 3, . . . and the wave-lengths can be represented by placing $t_1 = 3$, and $t_2 = 4, 5$ . . . in the above formula.

Only two lines of the infra-red series were discovered by Paschen with wave-lengths of 18,751 A and 12,818 A, respectively. Taking advantage of a very long hydrogen tube by means of which Wood at Johns Hopkins University had photographed in the laboratory twenty lines of the Balmer series, Brackett[1] was able to measure the wave-lengths of five members of the infra-red series, two of which had been observed by Paschen, while three of them were new. These five lines represent the fall of the electron into the third orbit from orbits 4, 5, 6, 7 and 8. Two lines of an entirely new series were likewise discovered by Brackett corresponding to an electron falling into the fourth from the fifth and sixth rings of the hydrogen atom. The wave-lengths of these lines are 4.05μ and 2.63μ, respectively. These four series of hydrogen, the Lyman series in the extreme ultra-violet, the Balmer series in the visible spectrum, the Paschen series in the infra-red and the new Brackett series in the far infra-red are in splendid agreement with Bohr's theory. The four series represent falls from outer orbits of electrons to the first, second, third and fourth rings, respectively.

On Bohr's theory there was no place in the hydrogen

[1] *Astrophysical Journal 56,* 154, 1922.

series for the lines discovered in 1896 by E. C. Pickering in the star ζ Puppis which lines appeared to converge to the same limit as the Balmer series of hydrogen and were closely represented by substituting $(t_2 + 0.5)$ for t_2 in the Balmer formula. The line 4686 A is also of the very greatest astronomical interest. It is found in many Wolf-Rayet stars and gaseous nebulae and is likewise found in the flash spectrum. When this line was discovered in the laboratory in 1912 by Fowler, in experiments on a helium tube in which hydrogen was present as an impurity, the line was ascribed to hydrogen. This identification, however, was not satisfactory. The theory of Bohr settled the question by demonstrating that the line 4686 A, and also the Pickering series, are not due to hydrogen but to ionized helium.

The neutral atom of helium consists of a nucleus carrying a net charge of two positive units and two outer negative electrons, the mass of the nucleus being four times that of the nucleus of the hydrogen atom. When the gas is subjected to discharges of moderate intensity, one of the outer electrons is displaced, and the spectrum of neutral helium is emitted when this electron falls in to different orbits on its return towards the nucleus. The theory of the production of the spectrum is not complete since the mathematical discussion involves that of the problem of three bodies. However, when the action of the stimulus is sufficiently strong, both electrons are supposed to be removed from the normal orbit. An entirely different spectrum is emitted when one of the two electrons returns, this being the spectrum of ionized helium. The formula for the series of lines is identical in its mathematical form with that of hydrogen. The factor 4 however enters into the constant for the reason that the nuclear charge is $2e$. Bohr's theory therefore shows that the 4686 line, supposed originally to be due to hydrogen, is in reality due to ionized helium. The Pickering series is also due to ionized helium, and as members of the same series there ought to be lines nearly coincident with the Balmer series of hydrogen. Some of these lines have been observed in the laboratory by Evans and by Paschen, and as the lines have been observed when all traces of hydrogen were absent, there is abundant support for the belief that the lines are actually due to helium and not to hydrogen. These lines of ionized helium have been measured by Plaskett in certain O-type stars. At the position of $H\alpha$ the difference in wave-length from the hydrogen to the helium line is 2.63 A, while at $H\theta$ this diminishes to 1.54 A.

It has thus been found that the enhanced spectrum of helium resembles that of neutral hydrogen, and in exactly similar manner it has been concluded that in all details (even in showing doublets or triplets in their spectra) the enhanced spectrum of an alkali earth (like Mg) resembles the arc spectrum of the alkali metal of next lower atomic number (like Na). It has further been concluded that this relation exists for all alkali earths and alkali metals. In fact, this similarity in spectra between neighboring elements in the periodic table appears to be a general rule, namely, that the enhanced spectrum of any element resembles the arc spectrum of the element of next lower atomic number. If an element loses two electrons, and is therefore doubly ionized, its spectrum, for the same reason, should be similar to the arc spectrum of the element of second lower atomic number. There is some indication of this doubly enhanced type of spectrum existing in C and Si, as shown by the work of Fowler, but the details have not been published. It therefore seems certain that the series relationships in various spectra have fully substantiated Bohr's theory of the formation of spectrum lines. The peculiarity of the Bohr atom is that it has been assumed that all of the orbits lie in one plane. It is therefore unexpected and surprising that this theory can furnish the exact quantitative agreement in wave-lengths that result from it. Although the mathematical analysis for a generalized theory is too difficult to follow through to completion, there is every assurance that spectrum analysis has been placed by this means on a very firm foundation.

CHAPTER XVII

THE IMPORTANCE OF IONIZATION

THE discussion of the results of the flash spectrum obtained in 1905 has shown the great importance of enhanced lines, or those due to the ionized atom, and the explanation offered at the time was that the cause of the enhancement was due to the great heights attained by the vapors producing the enhanced lines, and consequently, to the reduced pressures at which these lines were found. It was also pointed out that at the time of an eclipse the light from the sun is capable of reaching us only in a direction tangential to the sun's surface. As a result, a beam of light from the bottom of a layer only 500 km in thickness would encounter no less than 25,000 kms of emitting atoms in the tangential line of sight before getting out of the shallow layer. Any theory that can explain the method whereby atoms are ionized will be of the very greatest importance in all problems of modern astronomy. Such a theory has been proposed by Dr. Megh Nad Saha of the University of Calcutta.

Accepting the correctness of the Bohr-Sommerfeld theory of atomic radiation, and assuming that the general laws of thermodynamics apply equally well to electrons and to molecules of gases, Saha has been able to calculate the degree of ionization that takes place in gases under different conditions of temperature and pressure, and has derived formulas which can readily be applied to conditions existing in the atmosphere of the sun and of the stars. This theory explains both qualitatively and quantitatively many of the features observed in the spectrum of the sun and of the stars, and it likewise finds a ready application in laboratory spectra under conditions when enhanced lines appear.

In addition to the original papers by Saha,[1] valuable contributions on the same subject have been made by Milne,[2] and by Russell.[3] Assuming that the decomposition of a molecule or an atom into one or more electrons and a positively charged ion is essentially of the same nature as an ordinary chemical reaction, Saha derives a simple equation to express the self-ionization of a gas at high temperatures. The equation derived is:

$$\frac{P\ x^2}{1 - x^2} = K$$

$x/(1 - x)$ is the ratio of the percentage of atoms ionized to those left neutral, and this ratio multiplied by the partial pressure of the free electrons ($P\,x/(1 + x)$) is equal to K, which is a function only of the absolute temperature of the gas and the ionization potential. This latter is a measure of the work done to ionize a single molecule, or to drive an electron from its neutral ring to infinity, and it is expressed as the number of volts through which the electron must fall to acquire this energy. The ionization potentials are known for a number of gases (*see* Hughes, Report on Photo-Electricity, *Bulletin of the National Research Council*, 1921). Since the ionization potential for a given gas is a constant, the quantity K, in the formula above, depends only on the absolute temperature. Hence for a given pressure, the smaller the value of the potential P, the more nearly x approaches unity, or in other words the more nearly complete is the ionization. For all gases where the ionization potential is known, Saha is enabled to calculate the percentage of ionization found under different conditions of temperature and pressure. The higher the value of the ionization potential, the higher must be the temperature to sustain a given degree of ionization. This is readily seen in the case of helium which possesses the highest known ionization potential, of 20 volts; for the Pickering series due

[1] *Philosophical Magazine*, *40*, 472 and 809, 1920; *Ibid*, *41*, 267, 1921; and *Proceedings of the Royal Society*, A, *99*, 135, 1921.

[2] *Monthly Notices, R. A. S.*, *44*, 261, 1921.

[3] *Astrophysical Journal*, *55*, 119 and 354, 1921.

to enhanced helium is found only in stars of the highest temperature.

Saha's theory was originally based on the condition that one gas only is present in the solar or stellar atmosphere, but Russell (*loc. cit.*) takes up the question of two or more gases, and amplifies Saha's conclusions.

Saha calculates tables giving the percentage of ionization in atmospheres at various temperatures and pressures (measured in atmospheres). The following tables are copied from his publication, for two of the elements, calcium and strontium, found in the sun.

PERCENTAGE IONIZATION OF CALCIUM

Pressure (atmos.) Temp.	10	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}
°						
4,000	0	0	0	3	9	26
5,000	0	2	6	20	55	90
6,000	2	8	24	64	93	99
7,000	7	23	68	91	99	100
8,000	16	46	84	98.5	100	100
10,000	46	85	98.5	100	100	100
12,000	76	96.5	100	100	100	100
14,000	90	100	100	100	100	100

PERCENTAGE IONIZATION OF STRONTIUM

Pressure (atmos.) Temp.	10	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}
°						
4,000	0	0	2	5	15	45
5,000	1	3	11	32	73	96
6,000	4	13	37	78	97	100
7,000	10	32	73	96	100	100
8,000	22	58	91	99	100	100
10,000	56	90	98.5	100	100	100
12,000	82	97.5	100	100	100	100
14,000	93	100	100	100	100	100

Saha applies his theory to explain the differences between the spectrum of the sun and the chromosphere, and Russell broadens the scope of the theory by applying it to show the meaning of the differences in intensities of lines in the sun-

spot and in the solar spectrum. The results furnish a complete triumph for the Saha theory.

Fortunately for the theory, the flash spectrum gives the height in kilometers (or miles), that the various vapors producing different spectral lines extend above the level of the sun's photosphere. Although we have no precise knowledge of the actual pressures that are found in the reversing layer of the sun, we do know that increase of elevation corresponds to diminished pressure. In a sense, therefore, we know qualitatively, if not quantitatively, the actual pressures. Our information regarding the temperatures to be experienced in the solar atmosphere is, however, more complete. According to Abbot,[1] the solar temperature is not far from 6000° C absolute. Schwarzschild[2] has shown that if the variation in temperature in the upper atmosphere is caused only by radiation, then the temperature should not fall below $6000°/2^{\frac{1}{4}}$, or 5000°, approximately. Hence in the solar atmosphere where the temperatures vary between 5000° and 6000°, it is easy to see at a glance from Saha's tables the percentage of ionization. For instance, in the chromosphere at elevations where the pressure diminishes to one ten-thousandth of an atmosphere, ionization for calcium is ninety percent complete.

Saha's theory is in complete harmony with the conclusions derived from the discussion of the flash spectrum and furnishes an adequate explanation. The case of calcium is most interesting. The lines H and K are enhanced lines and are caused by the ionized atom, while the *g* line at 4227 Å takes its origin from the neutral atom. In the neighborhood of the reversing layer, both normal and ionized atoms will be plentiful and the presence of *g* and the H and K lines are fully explained. At great heights above the reversing layer, however, the pressure will be very small, and as a result, ionization will be nearly complete. Under these conditions the neutral atom cannot exist, the ionized atom exhibiting the enhanced lines alone being found. In the flash spectrum, measures indicate that the H and K lines extend upwards

[1] *The Sun*, p. 116.
[2] *Gott. Nachrichten*, *41*, 1906.

to heights of 14,000 kms, but the *g* line only to 5000 kms. The presence of H and K above the 5000 km level shows that calcium actually exists above this level, and we must therefore interpret the failure of the atom to emit the *g* line above the 5000 km level to be due to the fact that practically all of the atoms are ionized and there are few normal atoms left to produce the 4227 line. For strontium and barium, which also exhibit enhanced lines, their ionization potentials (5.7 and 5.1 volts) are lower than that of calcium (6.1 volts), and consequently complete ionization in the chromosphere is found at higher pressures, or in other words, at lower elevations above the photosphere. The strongest line of neutral *Sr* is 4607 A, which reaches an elevation of only 350 km, while the ionized atom *Sr+* shows the two lines at 4215 A and 4077 A which are found at elevations much greater than that of the neutral atom, in fact, at 6000 km, but this level is much less than the 14,000 km height attained by the H and K lines of *Ca+*. And so with barium. The neutral atom producing the line 5535 A reaches a level of only 400 km, while the enhanced lines 4934 A and 4554 A reach elevations of 750 and 1200 kms respectively.

For complete knowledge of the conditions affecting lines in the spectra of the sun, chromosphere and sun-spots, it is necessary that spectral series originating in both the neutral and ionized atoms be known for the different chemical elements. In the chromosphere, the ten elements represented by the greatest number of lines are in order: *Fe, Ni, Ti, Mn, Cr, Co, C, V, Zr* and *Ce*. It is probably on account of the great richness in lines of these elements that it has been impossible up to the present to sort the spectral lines of these elements out into series; but we can confidently look forward to the future to accomplish this. Since series relationships are known for very few of the chemical elements, it is evident that a detailed comparison of the ionized and neutral atoms is possible for a restricted number of the elements. As a matter of fact, the only elements represented by strong lines both in sun and in chromosphere, and for which series for both neutral and ionized atoms are known, are found in

Group I of the periodic table, the three elements *Ca, Sr* and *Ba*. In the following table there are given the details concerning the ***strongest*** single line found in the neutral series of each of the three elements, and also the ***strongest*** doublet belonging to the ionized atom. In the second column is given the wave-length and in the last the heights in kilometers measured in the flash spectrum. In the four other columns are given the intensities in sun, chromosphere, arc and spark, respectively, all values being taken from the *Publications of the Leander McCormick Observatory, 2*, pt. 2. The intensities of the lines of the chromosphere are given on a scale where 100 represents the strongest line, while Rowland's intensities in the sun are on a different scale, of 1000 as the maximum strength. Although series are not known for the element scandium, the details are given for the two strongest lines belonging to this element. From the intensities of arc and spark, it is evident that the *Sc* line 4247 is enhanced, while 4325 is not. The vastly greater heights attained for each element by the enhanced lines are evident at a glance. The symbol + designates the ionized atom.

Comparisons of the Strongest Lines of the Neutral and Ionized Atoms

Element	Wave-Length	Sun	Chromo-sphere	Arc	Spark	Height in km.
Ca	4227 (g)	20	25	1000	100	5,000
Ca+	3933 (K)	1000	100	500	1000	14,000
Ca+	3969 (H)	700	80	300	500	14,000
Sr	4607	1	2	1000	50	350
Sr+	4077	8	40	1000	1000	6,000
Sr+	4215	5	40	500	500	6,000
Ba	5535	2	1	100	30	400
Ba+	4554	8	20	1000	1000	1,200
Ba+	4934	7	12	100	300	750
Sc	4325	4	6	20	20	750
Sc+	4247	5	30	50	100	6,000

This small table contains some of the conclusions derived from a study of the flash spectrum which, on account of their importance, will bear being repeated. The strongest line in the Fraunhofer spectrum is K (Rowland intensity 1000) and this line is the strongest in the flash spectrum (intensity 100 on a different scale). The enhanced lines which are produced by the ionized atom (designated by +) have an intensity in the chromosphere greater than in the sun, and the enhanced lines extend to greater elevations above the photosphere than do the ordinary or unenhanced lines.

Other elements, in addition to those in the above table, produce lines stretching to moderate heights in the chromosphere. Omitting from present consideration the elements hydrogen and helium, there is given an additional table of lines attaining an altitude in the chromosphere of 1000 kilometers or greater. Only lines are included where it was possible to confine the identification of the spectrum line to one element only (the line not being a blend). Of the greatest interest, perhaps, is the comparison of the behavior of the two elements *Fe* and *Ti*, which are represented by numerous and strong lines both in the sun and in the chromosphere. Of the total of 19 *Fe* lines found at elevations of one thousand kilometers or more, only two lines are enhanced, those at 4924 A and 5018 A; while on the other hand, every line but one of the 17 *Ti* lines is enhanced. Although in the Fraunhofer spectrum the *Fe* lines have twice the average strength of the *Ti* lines (in the special lines under consideration, intensity 13 against 6), the *Ti* lines are twice stronger than the *Fe* lines in the chromosphere (20 against 10). The elevation of the *Ti* lines in the chromosphere average more than twice the altitudes attanied by iron. These facts bear out the conclusions[1] drawn many years ago that "on the average a *Ti*-line of any given intensity in the sun, say 5, will have a stronger line in the chromosphere corresponding to it than an *Fe*-line of the same intensity."

[1] *Astrophysical Journal, 38,* 487, 1913.

ADDITIONAL LINES WHICH ATTAIN MODERATE HEIGHTS IN THE CHROMOSPHERE

Element	Wave-Length	Sun	Chromosphere	Arc	Spark	Height in km.
Na	5890 (D_2)	30	10	1000	10	1000
	5896 (D_1)	20	10	1000	8	1000
Al	3944	15	15	800	15	2000
	3961	20	20	1000	100	1500
Mg	3829	10	20	30	200	6000
	3832	15	30	50	300	6000
	3838	25	40	100	500	7000
	5172	20	20	50	30	1000
	5183	30	25	100	100	1200
Fe	3720	40	10	50	10	1500
	3763	10	4	20	6	1000
	3767	8	8	15	5	1000
	3820	25	10	50	10	1200
	3824	6	8	20	5	1000
	3826	20	8	20	5	1000
	3840	8	5	15	4	2000
	3841	10	5	15	6	2000
	3860	20	20	20	6	6000
	3895	7	4	10	3	1200
	3899	8	3	10	4	1000
	3920	10	6	10	4	1000
	3923	12	8	10	15	1200
	3928	8	10	15	4	1000
	3930	8	8	15	4	1000
	4045	30	15	50	15	1000
	4383	15	15	100	20	1600
	4924	5	20	....	8	1000
	5018	4	15	1	7	1200
Average *Fe*	19 lines	*13*	*10*	*23*	*8*	*1442*
Ti	3373	10	12	4	20	1000
	3685	10	40	8	100	6000
	3741	4	15	3	10	1500
	3759	12	45	10	20	6000
	3761	7	40	6	10	6000
	3840	8	5	15	4	2000
	3900	5	10	5	50	1600
	3913	5	20	5	20	2000
	4290	2	15	2	10	1300
	4294	7	15	2	10	1200
	4300	5	15	3	8	1200
	4395	5	25	10	20	2500
	4444	5	20	4	15	1600
	4468	5	20	4	15	1500
	4501	5	20	4	15	1600
	4563	4	15	3	10	1200
	4572	6	20	5	20	1200
Average *Ti*	17 lines	*6*	*20*	*5*	*21*	*2900*

A comparison of the spectra of the sun and the chromosphere reveals the following facts (Chapter XIV): first, the values of Rowland, giving the intensities of the lines of the ordinary solar spectrum, are comparable with arc intensities, while those of the chromosphere approximate more closely to the intensities of the spark; and second, the enhanced lines of any element are in every case stronger in the chromosphere than the lines of the neutral atom, and the heights attained are much greater. The results are a complete verification of Saha's theory that enhanced lines are caused by ionization which becomes more and more complete in the sun's upper atmosphere where the great altitudes make the pressures very small. Lockyer's assumption that the spark is hotter than the arc and that enhanced lines are produced mainly as the effect of temperature has led to impossible conclusions, for to explain the enhanced lines in the chromosphere as a consequence of this theory it was necessary to assume that higher and still higher temperatures were reached at greater and greater distances away from the photosphere!

Saha's theory thus readily explains the formation of enhanced lines by ionization under reduced pressures. As soon as more complete information is secured regarding the ionization potentials of the various gases in the sun's atmosphere, particularly for such elements as *Fe* and *Ti*, and more accurate formulas are deduced for ionization under the conditions where more than one vapor is present, we shall undoubtedly be in a position to investigate very thoroughly the pressures found in the chromosphere at different elevations above the photosphere. An adequate solution of this problem will be a great achievement in solar physics.

The only information at present available regarding elevations in the chromosphere comes from the 1905 eclipse spectra. These photographs of the flash, which were taken at sun-spot maximum, should be supplemented by plates taken at sun-spot minimum, which will be possible at the eclipse of 1923. It is confidently hoped that spectra with good definition and large dispersion will be secured in 1923. Eclipse results should also be supplemented by photographs

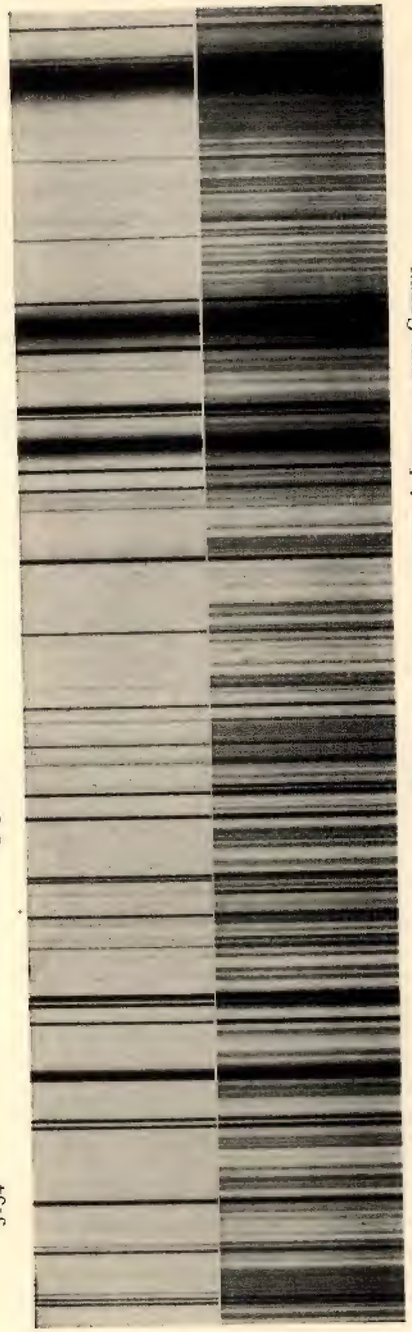
of the flash spectra taken without an eclipse. It is therefore again urged upon the astronomers, who are at present engaged in the determination of the sun's rotation by spectroscopic methods, that they devote part of their energies to the securing of photographs of the flash spectrum without an eclipse. Fox has already secured valuable results in measuring the heights attained by some of the stronger Fraunhofer lines by employing the 40-inch Yerkes refractor for this purpose.

Not only is Saha's theory able to explain the facts regarding the enhanced lines of the ionized atom, but it makes clearer the details concerning the lines of the neutral, or un-ionized atom. Take, for example, the D-lines of sodium, so well known in the Fraunhofer spectrum. At pressures below one-thousandth of an atmosphere, *Na* with an ionization potential of 5.1 volts, is completely ionized. The D-lines belong to the principal series of the normal atom, and accordingly, they have no connection with, and are not produced by the ionized atom. The normal atoms forming the D-lines therefore cannot exist when the pressure in the chromosphere is reduced to the thousandth of an atmosphere. It is quite in keeping with theory to find the flash spectrum photographs furnishing the information that the D-lines reach the comparatively small heights of only 1000 kms above the photosphere (H and K are found at 14,000 kms). The contrast in behavior in passing from the Fraunhofer to the flash spectrum for the D-lines of sodium on the one hand, and D_3 of helium on the other, is very marked. The sodium lines are weakened in the flash while the helium line is enormously strengthened, being entirely lacking in the ordinary solar spectrum. Furthermore, in view of the great prominence of the D-lines in the solar spectrum, it has always been a matter of the greatest surprise that the element potassium, so similar in its properties to sodium, is not found represented by strong lines in the sun. The explanation is a very simple one. The lines of the neutral atom of potassium, corresponding in its series to the D-lines of sodium, are found in the deep red part of the spectrum at wave-lengths 7664 A and 7699 A, and con-

sequently they are not in the visible spectrum. Like the D-lines, both lines of this pair are strengthened in sun-spots. The only lines due to potassium found in the visible solar spectrum are very weak lines at 4044 A and 4047 A, of Rowland intensities 0 and 00, respectively. Russell finds both these lines strengthened in sun-spots. No enhanced lines are known for *Na* or for *K*, and consequently neither element is conspicuous in the flash spectrum.

The temperature of the photosphere is approximately 6000°, while that of sun-spots is lower and probably somewhere near 4000°. The pressures found in sun-spots can differ but little from those in the lowest depths of the reversing layer. On account of the lower temperatures in the spots, however, ionization is less complete according to Saha's theory. As a result, the lines of the neutral atom, the so-called "low temperature" lines, are strengthened in sun-spots, while on the other hand, and also as a direct consequence of Saha's theory, the enhanced, or "high-temperature" lines are weakened in the spectrum of sun-spots. Since the variations in pressure in the neighborhood of the sun are much greater than the variations in temperature, it would have been more fortunate if the enhanced lines had been referred to as "low-pressure" rather than as "high-temperature" lines.

In the light of Saha's theory, Russell has investigated the sun-spot lines. His conclusions for the alkali metals (*loc. cit.* p. 129) are here briefly given. Sodium is represented in the sun by the principal, diffuse and sharp lines of the neutral series, and all of its lines are much strengthened in the spot spectrum. Potassium is represented by the principal series only and its lines are also strengthened in sun-spots. Lithium is found in the spot spectrum only at wave-length 6707 A. Rubidium, hitherto unknown in the sun, was discovered to be present by both members of the strongest pair of the principal series, the wave-lengths being 7800 A and 7947 A. If caesium is ever found in the sun, it will be only by means of sun-spot spectra and the only lines that will be discovered will be at wave-lengths in the infra-red at 8521 A



SPECTRUM OF SUN AND SPOT IN THE REGION OF THE *b* LINES IN THE GREEN.
Note the differences in intensities of the lines in the two spectra. The scale is that of Rowland's map.

and 8943 A. These lines correspond to the pair of the principal series of rubidium.

It has been recognized for a number of years that the sun-spot spectrum differs from that of the sun for two reasons: the strengthening of the low-temperature lines and the weakening of enhanced lines in the spots. It is now recognized for the first time that the spectrum of the chromosphere differs from the Fraunhofer spectrum likewise in two respects, and not in one only. The increased strength of the enhanced lines in the flash spectrum has repeatedly been emphasized, but not the diminution in strength in the chromosphere of the lines of the neutral atoms, the low temperature lines. Since the sun is a dwarf star, the spectra of chromosphere, sun and sun-spots represent a sequence in spectral types, the chromosphere being an "earlier" type and the sun-spot spectrum a "later" type of spectrum than that of the sun. According to the estimation of Miss Annie J. Cannon, the approximate Harvard classification of the three spectra are: chromosphere = Fo, sun = Go, and sun-spot spectrum = Ko.

We are now in a position to explain some of the peculiarities regarding the appearance of lines in the spectrum of the sun and chromosphere and the heights found in the flash spectrum. The peculiarities noted (Chapter XIV) are as follows: The H and K lines of calcium of atomic weight 40 are stronger in sun and chromosphere and reach greater heights than hydrogen, the lightest gas in the sun. In the chromosphere the whole Balmer series for hydrogen is found, while only the first four members are seen in the Fraunhofer spectrum. No helium lines are found in the ordinary solar spectrum, but they are of great strength in the chromosphere. The elements, other than *H* and *He*, arranged according to the periodic table of the elements have remarkable progressions in the number and intensities of the lines involved. Group II, the alkali earths, represent the strongest lines in the chromosphere, the strongest lines of all belonging to *Ca*. Group I, the alkali metals, have few strong lines in sun or chromosphere other than the D-lines of *Na*. None of the lines of Group O originating from the

inert gases Ne, A, Kr and Xe are found in sun or chromosphere. In Group III, strong lines are found for Al, Sc, Y, and the rare earths, but the strength of lines is not as great as reached by the corresponding elements in Group II. In Group IV intensities are still less. The only element in Group V, found with certainty in the chromosphere, is vanadium, and in Groups VI and VII, Cr and Mn, respectively, and in Group VIII, the three metals Fe, Co, and Ni.

It is easy to see why the metals of Group I, the alkalis, are represented by such feeble lines in the chromospheric spectrum. For reasons already stated, the enhanced spectra of the alkali metals resemble the spectra of the neutral atoms in the preceding group in the periodic table, the inert gases; and consequently, such spectra are very difficult to produce on account of the outer electrons forming part of a very stable ring or shell. As a matter of fact, no enhanced lines are found for any of the alkali metals in the visible portion of the spectrum. It is apparent, therefore, why the alkali metals cannot be prominently represented in the chromosphere since the flash spectrum is essentially an enhanced spectrum.

Quite different is the situation regarding the elements of Group II, the alkali earths, which are specially important in the chromospheric spectrum, for the reason that the strongest lines of their spectra are enhanced lines, and the principal members (1s — 2p) of the series lie in the familiar portion of the spectrum. This is true for the elements with the exception of Mg, the strongest lines of which are found in the extreme ultra-violet at 2795 A and 2802 A, in a region in fact where no light can reach the earth's surface from the sun on account of the absorption of light in the earth's atmosphere. Apparently therefore, the alkali earths will furnish the best tests for mapping pressures in the reversing layers at different elevations above the photosphere. To secure complete information regarding pressures in the sun's atmosphere it will, however, be necessary to investigate the actions of as many of the chemical elements as possible. Unfortunately at the present time no series are known, and no values of the ionization potentials have been ascertained,

for some of the most important elements represented by many lines in the solar spectrum. Such elements are Sc, Ti, V, Cr, Mn, Fe, Co, and Ni.

The great strength of the H and K lines of calcium both in the sun and in the chromosphere and the great heights to which these lines extend in the flash spectrum are now completely explained as the result of Saha's theory. In spite of the great difference in the atomic weights of the two gases, calcium and hydrogen, the atomic weight of the former being forty times the latter, the spectrum lines of calcium are seen to reach greater heights than are attained by hydrogen. The reasons for this curious circumstance are very simple. H and K are lines due to the ionized atom, and in virtue of the great elevations the ionization is greatly increased. The lines H and K are the chief lines belonging to the principal series, and in fact are the only lines of this series in the chromosphere. The two lines of the subordinate series of $Ca+$ at 3706 A and 3736 A are found in the flash spectrum also, but at greatly diminished intensities and heights (750 km and 1500 km, respectively). These four lines are the only lines in the flash spectrum belonging to $Ca+$. The hydrogen lines on the contrary do not belong to the ionized atom but to the neutral atom, and moreover the lines of the Balmer series, the only series of hydrogen in the visible spectrum, belong to a subordinate series and not to the principal one.

Other features connected with the hydrogen lines find their explanation from the Saha theory, namely, the reasons why only four lines are found in the Fraunhofer spectrum while the whole Balmer series to the number of thirty-five lines is shown in the chromosphere. Closely related is the fact that helium lines appear in the flash spectrum, but not at all in the ordinary solar spectrum. Dr. Saha has formulated his ideas in regard to this interesting question. He has kindly given permission that these matters be discussed here in advance of publication by himself.

Suppose we have a black-body surface at temperature T having in front of it a layer of radiating gas at the temperature T^1. Let λ be the wave-length of one of the characteris-

tic lines of the gas, I the emissivity of the black body at this wave-length, I^1 the corresponding emissivity of the gas and α the absorption coefficient of the gas. Then suppose the density of the layer to be uniform. It can be shown that the total absorption A is given by the formula,[1]

$$A = \left(1 - e^{-\alpha t}\right)\left(1 - \frac{I^1_0}{\alpha I_0}\right)$$

where t = thickness of the absorbing layer. If t^1 is the thickness of the emitting layer, then the total emissivity of the gaseous layers is

$$E = \frac{I^1_0}{\alpha}\left(1 - e^{-\alpha t^1}\right)$$

These two formulas, though imperfect (because the variation of density with height has not been taken into account), may be applied to the study of Fraunhofer absorption and chromospheric emission.

α, the absorption coefficient, is proportional to the number of absorption centers present, and therefore to the probability of absorption by the line. For *heavy* absorption lines like C, F, H, or K, $e^{-\alpha t}$ is zero, and hence

$$A = \left(1 - \frac{I^1_0}{\alpha I_0}\right)$$

As long as $\frac{I_0^1}{\alpha}$ is less than I_0, the absorption is considerable. But with increasing temperatures $\frac{I_0^1}{\alpha}$ may be $\geqq I_0$, and then the degree of absorption would diminish. With still greater increases in temperature, A may ultimately become negative and the spectral line will then appear bright on a continuous spectrum (as is the case with Novae).

For *faint* Fraunhofer lines, the depths of the layers are very small and hence the quantity t^1 may not be sufficiently great for *saturation,* i.e., for $e^{-\alpha t}$ to become zero. If α is very small, which will be the case for the subordinate atomic combinations, then there must be a larger value of t, the thickness of the layer, before sensible absorption may be produced. In the case of helium, the density of the gas is so small that the effective value of t fails to reach the saturation value. $e^{-\alpha t}$ never reaches a small value, it is almost unity, and as a result the absorption of helium is a negligible amount.

[1] Wood, *Physical Optics,* 592, 1914.

At the time of an eclipse, however, or when looking at the chromosphere in a tangential direction, the effective value of t (as already stated) is enormously increased in amount. In fact, t now becomes so great that $e^{-\alpha t}$ may become almost zero, and then the total emission will amount to

$$\frac{I_0^1}{\alpha}$$

For lines of subordinate combinations, both I_0^1 and α are small, but on account of the exaggerated layer which is presented to us, the integrated emission may assume rather large values. In this manner we have a satisfactory explanation of the absence of helium lines in the Fraunhofer spectrum and of their presence as emission lines in the flash spectrum.

Wood[1] has shown that an extreme vacuum is favorable to the production of the higher members of the Balmer series of hydrogen. This fact is quite in line with modern atomic-thermodynamical considerations. The Fraunhofer spectrum is mainly the result of contrast between the photospheric emission and emission from a shallow layer next to it. As in the case with helium, the stimulus of the hydrogen atom which belongs to a subordinate series is not sufficiently great to cause absorption strong enough for the production of any but the first four lines of the series, though all the lines of the Balmer series appear as emission lines.

The theory outlined just above is not confined it its applications to the formation of the hydrogen and helium lines alone, nor is it concerned only with the differences between the ordinary and the flash spectrum. It has an application much wider in its scope, for it seems to provide an explanation of the sharpness in outline of the dark lines which is

[1] *Proc. Roy. Soc. Lond.* 1920.

visible throughout the solar spectrum. The ionization of a gas makes it opaque, or in a condition where it cannot transmit radiation. It seems probable that at a depth in the sun where the pressure is approximately 0.001 atmospheres (terrestrial), the ionized gas is sufficiently opaque to prevent radiation from further down in the sun passing through this ionized layer and reaching the outermost regions of the reversing layer. Consequently, the major portion of the absorption forming the Fraunhofer lines takes place within the confines of the layer which is comparatively shallow in depth. Moreover, the elevation at which this ionized layer is found, varies not only with the different chemical elements but changes with spectral lines of different intensities of each of the elements. It is quite reasonable to suppose, from the above theory, that the ionizing layer for a strong line of any element, say a *Fe*-line of intensity 10, will be found at a greater elevation above the average level of the photosphere than a *Fe*-line of smaller intensity, such as 4.

Thus a rational explanation is derived for the conclusions of a previous chapter: (1), that strong lines in the Fraunhofer spectrum take their origin at a greater average elevation than weaker lines of the same element; (2), that the elevations vary from chemical element to element; and (3), the enhanced lines are found at greater heights than the ordinary lines in the spectrum of the same element.

It is manifest that having the information furnished by the theory of ionization and being armed with tables of enhanced lines, such for instance as Fowler's *Report on Series in Line Spectra*, we are able very quickly to tell whether or not a given element is present in the spectrum of the chromosphere. Take radium, as an example. A dozen years ago there was much discussion over the question, Dyson having found flash spectrum lines due to radium, while Evershed and Mitchell took the opposite stand. The strongest lines of the principal series of enhanced radium are at 3814 A and 4682 A, while three lines belonging to the diffuse series are at wave-lengths 3649 A, 4340 A and 4436 A. These are the *strongest* lines of *Ra*+, and if radium is in the chromosphere, we should unquestionably expect it to display its presence by these wave-lengths. As shown in *Popular Astronomy, 21*, 321, 1913, each of these five lines is already satisfactorily identified by coincidences with lines in Rowland's Tables, without invoking radium as a source. If therefore, we are to prove that radium is in the chromosphere, it will be possible only as the result of flash spectrum photographs with much greater dispersion than those taken in 1905. The only possible method of securing sufficiently great dispersion will not be at the time of an eclipse, but rather under conditions in a fixed observatory without an eclipse.

The case of the element *Mg* is interesting and peculiar. In the chromosphere appear the three lines of the well-known *b*-group in the green, and also a triplet in the violet at 3838 A, 3832 A and 3829 A; these lines forming the chief lines in the sharp and diffuse series, respectively. No other triplets are known in the region covered by the flash spectrum. All of the stronger single lines of *Mg* are also found in the chromosphere. In fact, every line listed by Fowler belonging to the triplet and singlet systems is found in the chromosphere. In view of the prominent role played by the lines of the neutral atom, one would naturally expect that the lines of ionized *Mg* would be specially brilliant, just as is the case with ionized *Ca*. The only line of *Mg*+ of any importance in solar and stellar spectra is the well-known 4481 A. In the flash spectrum there is a line at this wave-length, but it is weak and in no respect does it rival the lines H and K of enhanced *Ca*. The reason is clear by referring to Fowler's tables. The line 4481 belongs to the *fundamental* series of ionized *Mg*, which series is difficult to excite, and it is moreover of the " combination " type where two internal changes have taken place subsequent to ionization. Consequently, this line is produced with the greatest difficulty, and therefore its presence only in the spectra of the hottest stars is thus explained.

Saha's theory thus interprets in a beautifully clear manner the systematic differences between the flash spectrum, the solar spectrum and the sun-spot spectrum. It goes much further, however, and furnishes the causes of the progres-

sion in type of the stars from the red stars of class M to the early types of B and O. Lockyer was the first to call attention to the change in the appearance of the lines H and K, very faint or even missing in late M stars, with a maximum intensity in the solar, or Go stars, and becoming faint again in early B stars and disappearing in certain O stars. Lockyer's interpretation, one of temperature only, was unsatisfactory. The hydrogen lines have their maximum at type Ao and are less intense in both the earlier and later types. The lines of neutral helium appear only in the stars of very early type, while the 4686 line and the Pickering series due to enhanced helium are found only in still earlier types. The conditions of appearance and disappearance of spectral lines due to ionization are calculable, and it has thus been possible to assign temperatures to stars of different types which are in substantial agreement with those derived from other lines of research. All of the difficulties have not been entirely cleared away, but there has been a great step forward.

The theory of Saha has many different applications in many departments of astronomical research. Space will permit the mention here of one other only, namely, its relation to spectroscopic parallaxes. Adams and his co-workers have measured the absolute magnitude of a star (from which the parallax is found) by estimating the relative intensities of certain arc and enhanced lines in the spectra under investigation. These differences in intensity depend on the degree of ionization in the star, which in turn depends on the temperature and pressure in the outer layers of the star's atmosphere, while the values of the temperature and pressure must be dependent on the mass of the star. Hence, we are forced to the conclusion along with Russell[1] that "the spectroscopic parallax will be correct only in the case of stars having a certain average value of the mass." Stated in other words, this means that the spectroscopic parallax of any individual star cannot be correct unless the star under consideration has an average mass for a star of that particular type. If this star has a greater or less mass than

[1] *Astrophysical Journal*, *55*, 238, 1922.

the average, the spectroscopic parallax will be systematically in error. But since the Adams parallaxes are based on the mean of the best trigonometric parallaxes, the spectroscopic and trigonometric parallaxes should agree well *in the mean* of a large number of stars. For statistical purposes involving many stars, the spectroscopic parallaxes should therefore give results with great accuracy, provided of course that they are based on a sufficiently large number of trigonometric parallaxes. For any individual star, however, the value of the parallax furnished by spectroscopic methods should be regarded with caution, especially if there is reason to believe the star is of greater or smaller mass than the average for that spectral type. By assuming that the spectroscopic parallax has a dependence on mass, we have a rational explanation of some of the peculiar differences between trigonometric and spectroscopic parallaxes. Two examples only of such differences will be given here, the parallaxes given being reduced to absolute values. The first case is for the brilliant star Arcturus, of type Ko. The following are among the values of the parallaxes:

Mean of Yale (heliometer) and Flint (mer. circle)	=	+ 0".075
Mean of Yerkes and McCormick (both photographic)	=	+ .091
Mt. Wilson spectroscopic	=	+ .158
Harvard spectroscopic	=	+ .209

For *Groombridge* 2875 of type K4, the photographic parallaxes of Allegheny and McCormick are + 0."030 and + 0."031 respectively, while the spectroscopic parallax of Mt. Wilson has the value of + 0."100.

For these two stars (and other examples might readily be given), the spectroscopic parallax greatly exceeds the trigonometric values. Both are stars of K type, and the Mt. Wilson curves connecting differences in spectral intensities with absolute magnitudes should be thoroughly well determined on account of the excellent character of the spectral lines and on account also of the large number of stars with well-determined trigonometric parallaxes. The trigonometric parallaxes for both stars are in fairly satisfactory accord, and the burden of the proof therefore rests on the spectroscopic parallaxes. Why do they differ

so radically from the trigonometric parallaxes? The explanation does not seem to be found in the accidental errors, but rather in systematic differences. Apparently the reason is that Arcturus is not a typical or average star of the Ko type, and accordingly, the spectroscopic parallax has a value which is too large for the simple reason that Arcturus has a greater mass than the average star for which the curves have been determined. The same is true of the star *Groombridge* 2875. In *B. A. N.* No. 19, Pannekoek uses the systematic differences between the spectroscopic and the trigonometric and hypothetical parallaxes as a means of securing a measure of the mass of the star.

In spite of these systematic differences which in a few cases are large in size, the spectroscopic parallaxes of Mt. Wilson agree with the average of the best trigonometric parallaxes with a surprising degree of accuracy.[1] These parallaxes are the expression of an empirical relation between the absolute magnitude on the one hand and spectral types and differences in line-intensity on the other. The physical basis underlying the spectroscopic method of determining parallaxes is not fully understood, but the beauty of the method is *that it works*. The absolute magnitude of a star is thus shown to be a function of two other quantities connected with the star. By empirical or other methods, it should be quite possible to derive similar relationships among others of the physical constants involved in the life of a star. Such conditions are mass, temperature, density and pressure in the atmosphere, absolute magnitude, apparent magnitude, etc. Can we not come to a general conclusion, and decide that the physical constants are not all independent and that relationships exist among them? Certainly so. In fact, it should be quite possible to connect any one quantity concerned in a star with two other independent quantities and to express the relationship by means of a function. Some of these functions will be simple in form. Seares [2] has given a list of seven simple relationships, Russell [3] has given two

[1] Strömberg, *Astrophysical Journal, 55,* 11, 1922.
[2] *Astrophysical Journal, 55,* 165, 1922.
[3] *Astrophysical Journal, 55,* 238, 1922.

others where the form of the function cannot be determined, and additional similar connections will be found by other authorities.

The past decade has witnessed a remarkable increase in knowledge in all departments of sidereal astronomy. Progress for the future will depend, as it has always depended in the past, on securing the observational data with as high a degree of precision as possible. The most important link in the chain of progress for perfecting our ideas of the system of the stars seems still to lie in the accurate determination of stellar distances.

The theory of ionization has shown the essential unity of astronomy, proving not only that the sun is a typical star but also that a study of the stars can shed much information on solar questions. The great problem of astronomy, the evolution of the stars and the structure of the universe, can find their complete solution only through an intimate study of the constitution of matter. The size of an atom can be deduced from observations of giant stars. The stars are laboratories, inaccessible to the physicist and the chemist, wherein great changes of temperature, pressure and electrical conditions may be studied at will. The structure of the atom and the theory of ionization are unquestionably among the most important problems of present-day science.

CHAPTER XVIII

THE CORONA

THE corona still remains exclusively an eclipse phenomenon. In spite of the amazing achievements of modern science which at times seems to be able almost to accomplish the impossible, no success has attended the efforts made to observe the corona outside of an eclipse. On account of the entrancing beauty of the phenomenon each eclipse is assiduously observed, but success commensurate with the labor involved is not always forthcoming.

According to the *Report of the Committee on Eclipses* presented to the American section, International Astronomical Union, 1922, "The problems of the corona are many, and few of them can be said to have approached solution. Important facts concerning it have been established, but these facts are more or less isolated, and in general their relations to each other are unknown. The paucity of results obtained thus far is due primarily to the unique condition that the most assiduous of eclipse observers can scarcely hope for more than an hour of totality with clear skies, in his entire lifetime."

In this and the following chapter an attempt will be made to give a synopsis of the present condition of the problems concerning the corona referred to in the above report.

No eclipse expedition worthy of the name will be fully equipped unless it has as part of its program the securing of large scale photographs of the corona. Astronomy of the future needs, as it has in the past, to secure good photographs of every possible eclipse. The Lick Observatory has the most complete series in existence, beginning with the eclipse of 1893. The Lick photographs have always been secured by pointing the camera directly at the sun, the method devised by Schaeberle, and a uniform focal

Composite Drawing of the Corona, August 30, 1905.
From photographs secured by the U. S. Naval Observatory expedition.
Drawn by Capt. H. W. Carpenter, U.S.M.C.
(In a black-and-white drawing the contrast is necessarily exaggerated.)

length of forty feet has been employed. This permanent record of the past is always available for purposes of comparison. In attempting to photograph the corona on a large scale, it goes without saying that the greatest care should be exercised to secure as perfect definition as possible, and also that the photographic manipulation should be conducted so as to bring out of the plates as much of the wealth of detail as possible. Development may be carried out in such a way as to attain very different photographic effects. If contrast is needed, as in spectrum work, a "hard" development is required. There are many developers suited for this sort of work with which anyone doing spectrum work is entirely familiar. For developing the corona, however, where it is necessary to bring out as many of the fine details as possible, and where an attempt should be made to minimize the contrast between the bright inner corona and the faint outer corona, an entirely different kind of developer and development is necessary. Old-fashioned "pyro" is probably the best form of developer to use for this purpose, and one would do best to start with a very weak solution and proceed gradually. The proper development of each plate will take at least an hour. Undoubtedly many well exposed coronal photographs have been spoiled through improper care in development.

The five-inch aperture, forty-foot focus generally used by the Lick Observatory parties represents a ratio of aperture to focal length of 1:96. The commercial photographer would look aghast if he were compelled to work with such a slow camera. For eclipse work of the future there will be used greater apertures and longer focal lengths. If focal lengths much greater than forty feet are employed it will be difficult, or well-nigh impossible, to use the direct mounting, and recourse must then be had to the horizontal telescope, and coelostat mirror for reflecting the light. Compared with the direct mounting, the horizontal telescope has the great disadvantage that the mirror is sensitive to changes of temperature and may change its shape on eclipse day when exposed to the sun's rays. Ordinarily, focus is obtained by star trails, and if possible a warm night should

be used. It is imperatively necessary to keep the mirror of the coelostat protected from the sun's rays on the day of the eclipse until a very few minutes before totality. The horizontal telescope is easier to construct and mount in the field. Care should be taken that the tube is not too near the ground. For the purpose of portraying the details of the corona it is evident that the greater the focal length utilized the more valuable will be the results. Cameras of medium and small size have not been superseded by the large instruments and still have useful functions at eclipses. Larger ratios of aperture to focal length are possible than with those of the largest size. Such cameras are more rapid, and consequently, are useful in securing the faint extensions of the outlying corona. They are especially valuable in photometric observations which will be taken up in detail below. Every precaution should be taken to reduce to a minimum the effects of halation and reflections from the glass-side of the plates. All plates used for photographing the corona should be "backed" with some absorbing material on the glass side. Some eclipse observers have had excellent success from using double-coated or triple-coated plates.

The general form of the corona can be predicted in advance of the eclipse. At sun-spot minimum are found the long equatorial streamers and the short plume-like polar brushes, while at sun-spot maximum the polar rays are longer and brighter, and the equatorial streamers shorter than at sun-spot minimum, the corona thus being more or less circular in shape. How long these typical shapes persist after the maximum or minimum phase is past is still undecided. Sun-spot maximum occurred in August, 1917. The eclipse of June, 1918, did not show the typical corona of sun-spot maximum, for the polar streamers were shorter than those near the equator, and the corona departed more from the circular shape than was actually anticipated. Generally when the maximum of spots is past, the streamers draw away from the poles, and the longest rays are found in the sun-spot zones, making the corona rectangular in appearance. A precise knowledge of the exact causes underlying these pronounced changes in shape is an accomplishment which still lies in the future.

Concerning the total eclipse of March 29, 1652, seen in Ireland, Dr. Wyberd writes, "The moon suddenly threw itself within the solar disk with such agility that it seemed to go round like an upper mill-stone. The sun then appeared around the limb, affording a pleasant and remarkable spectacle of rotation." There seemed to be a wide-spread notion among the early observers of eclipses that during totality very rapid motions took place within the corona and that the corona was some sort of a modern fireworks display with brilliant scintillations and sudden changes. In fact, the early notion seems not to have entirely vanished in the enlightened and scientific age of the twentieth century.

Although it may be said with truth that the shapes of the corona at minimum of sun-spots all resemble each other in having long equatorial streamers and pronounced polar brushes, yet each corona has its own particular features, its own peculiar structure. The coronas of 1878, 1889, 1900 and 1922, all taken at minimum phase of sun-spots, could never be mistaken one for the other. In fact there were two eclipses in the year 1889, on January 1 and December 22, with very pronounced alterations in shape in the coronas. These variations in form, as pointed out by Wesley,[1] were precisely in accordance with the change to be expected with the sun returning toward a condition of spot activity. The coronas at or near sun-spot maxima resemble each other even less than do the different aureoles at sun-spot minima. The coronas corresponding to maximum of spots are, it is true, approximately circular in outline, but prominent rays and streamers shoot out at various angles. We are therefore forced to the conclusion that changes are continuously going on in the corona. How rapid are these changes? Can they be detected from photographs taken with the same camera, at the beginning and ending of a total eclipse? It is possible that the few short minutes of totality may afford too short an interval to permit these changes to be detected with certainty, from photographs taken at any one

[1] *Observatory*, No. 160.

location, but motions might possibly be detected from photographs secured at widely separated stations at the same eclipse.

Any theories dealing with coronal structures must depend on the measured changes within the corona itself, and it is therefore imperatively necessary that reliable information be secured regarding these motions. The importance of this problem has been fully recognized by eclipse observers for many a long year. Manifestly, no real progress was possible as long as it was necessary to depend for information on drawings of the corona. In fact, sketches made during the time of an eclipse have been a continued disappointment, but the non-success was no greater than what should have been expected. Even a skillful draughtsman subjected to the excitement and unfamiliarity of a total eclipse could not be expected to see and draw, in the hurried interval of a couple of minutes, more than a few details of coronal structure. These details of necessity must be exaggerated in the drawing. A sketch made by a second person, as well trained as the first draughtsman and secured at the same time and location, probably would stress other details regarded as important. But to make matters worse, most of the drawings of the corona made in the past were secured by men who were observing their first eclipse, and frequently these very men had little experience or skill in the making of sketches. With the advent of the photographic plate, the wholesale drawing of the corona during totality has been pushed more and more into the background.

To detect motions in the corona with the greatest certainty, several prerequisites are necessary: First, the photographs to be measured should be on as large a scale as possible; second, the interval in time should be as great as possible; and third, the photographs to be compared should be secured with cameras of nearly the same focal length and they should resemble each other in general appearance as much as possible. Plates developed with different effects of contrast and taken under different conditions of seeing cannot furnish motions with the highest degree of precision.

Attempts were made as early as 1889 to secure the necessary information by the comparison of photographs at the eclipse of December 22. An interval of two and a half hours elapsed between the time of totality at Cayenne and Cape Ledo in West Africa. Unfortunately, clouds were experienced at the latter station. As a result of the long duration of totality at the eclipse of 1901, an exceptionally favorable opportunity existed for determining motions from observations at a single station. Perrine [1] secured successful photographs with the 40-foot camera. Measures of short exposure negatives, taken near the beginning and end of totality, showed no displacements of coronal masses in the interval of a little more than five minutes. On account of the accuracy of the measurements, it was possible to have measured with certainty a velocity of 20 miles per second across the line of sight. Motions should have been suspected if they had been as great as 12 or 15 miles per second. The 1901 photographs were near sun-spot minimum. At the eclipse of 1905, Hansky secured photographs on the same scale as Perrine's photographs.[2] The corona was one of typical maximum form and presented few conditions for the best results. The corona was very intense, especially near the solar surface, and its rays, being projected from all sides of the disk of the sun, so superposed themselves the one upon the other and became so entangled that it was almost impossible to distinguish the same details on successive photographs. By taking the original negatives and making glass positives, by proper shading and by local development, much detail was secured in the corona. From the measures of 43 separate rays, information was obtained concerning the motions of the coronal material within the period of totality lasting a little more than three minutes. The velocities determined were little greater than the errors of observation. None of the velocities investigated exceeded 25 km per second.

In accordance with the plans of the Lick Observatory of always attacking eclipse problems of the greatest importance, an attempt was made at the eclipse of 1905 to detect

[1] *Lick Observatory Bulletin*, *1*, 151, 1902.
[2] *Mitt. Pulk.*, *2*, No. 19, 107.

changes in the coronal structure by establishing three stations at widely separated localities and securing large-scale photographs at each station. Parties were sent to Labrador, to Spain and to Egypt. Unfortunately for the success of the scheme, cloudy weather prevailed in Labrador where were stationed Curtis and Stebbins. Thin clouds were met in Spain, but they did not greatly interfere with the photographs secured by Campbell and Perrine. Clear skies greeted Hussey in Egypt where totality occurred 70 minutes later than in Spain. A careful comparison was made of the photographs [1] secured at the two stations. A number of fairly well-defined nuclei were found, both east and west of the sun. Details of structure within the nuclei appeared to change, but the nuclei as a whole remained in the same position. Measures of the greatest accuracy were impossible on account of the poor definition of the Egyptian plates caused by poor seeing. The conclusion was that " the masses in question could not have moved so much as one mile per second during the interval of 4200 seconds. Greater speeds might well have occurred within the principal coronal streamers, or within some of the arched forms which enclose prominences, without our having detected them; for their structure is quite uniform, and well-defined nuclei are absent."

The American eclipse of 1918 afforded an additional opportunity by comparing plates taken at three separate stations where were located expeditions from Lick, Lowell and Sproul Observatories. At Goldendale, Washington, the focal length was 40 feet, at Syracuse, Kansas, the camera was 38.7 feet in length, while at Brandon, Colorado, the camera was 62 feet long. One plate secured by each of the first two cameras and two plates with the 62-foot instrument were compared. Each of the three cameras pointed directly at the sun. There were no definite nuclei or other distinctive features present in the streamers that were sufficiently well defined to be used as points of measurement by Miller.[2] There were, however, three arches

[1] *Lick Observatory Bulletin, 4*, 121, 1907.
[2] *Publ. A. S. P., 32*, 207, 1920.

surrounding three prominences and attention was confined to these. The first arch was around the " Pyramid " or " Eagle " prominence in the northeastern quadrant. Towards the pole side of this prominence there were four well-defined arches. The second arch was around a prominence in the SE quadrant, while the third arch was near the " Skeleton " prominence. Each of the three prominences displayed four separate arches, and the positions of one arch only of each were measured. These measures gave fairly accordant results and seemed to show that the arches had changed in the twenty-six minutes' interval between the Lick and the Sproul photographs. The average rate of speed at which these arches receded from the sun was about ten miles per second.

From the photographs compared by Miller, it was evident that the polar rays east of the axis of symmetry are curved away much less than the rays to the west, the difference not being due to the effect of projection. It is therefore evident that the velocities with which material is ejected from the sun to form the coronal streamers must be very small compared with the motions with which we are familiar in the prominences. Any theory dealing with the formation of the coronal structure must take cognizance of these moderate velocities of ejection.

The corona owes its entrancing beauty to the far-flung, pearly-white streamers, so conspicuous in each corona observed. The contrast with the rosy-red prominences close to the edge of the black moon makes a never-to-be-forgotten spectacle. In addition to the streamers, there are other features of the corona that deserve attention, and it is necessary to find out their relations to solar phenomena such as prominences, sun-spots and faculae. " Arches," " hoods " or " striated cones " have been observed since Cleveland Abbe first saw them at the eclipse of 1869. They are specially conspicuous at the time of sun-spot maximum. The first good photographs obtained of them were by Schaeberle at the eclipse of April, 1893. The coronal arches were noted by him [1] to be associated with prominences.

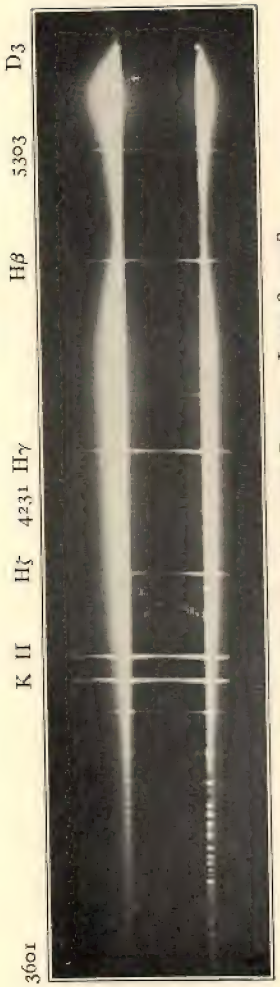
[1] *Contributions from the Lick Observatory, 4*, 94, 1895.

Miss Clerke[1] draws the conclusion that "Each pearly pavilion is erected over a red flame. Coincidences of the kind are of perpetual occurrence." These hoods were specially marked in the coronas of 1896 and 1898, but were practically missing from the minimum type of corona of the year 1900.

At the eclipse of 1901, a different kind of "disturbance" was noted in the photographs secured by Perrine, which consisted of a conspicuous center, apparently at the sun's limb, from which strong streamers stretched out to great distances from the edge of the sun. This disturbance was all the more interesting for the reason that Perrine found it to take its origin over the region of a prominent sun-spot. In fact, this spot was the only one known to exist on the sun at the time. Similar disturbances were seen in the photographs of the eclipse of 1918, but Campbell and Moore could find no relation between them and any sun-spot or chromospheric phenomena known to exist on the sun. As already stated, the arches were specially prominent at this recent eclipse and they extended to much greater distances from the sun's limb than they did in 1893, although both eclipses were near sun-spot maximum. Miss Clerke's opinion that the coronal hoods are intimately associated with prominences seems to be thoroughly well substantiated. They are much more conspicuous in the coronas seen at maximum of sun-spots for the reason that prominences are much more numerous and active and are found in all heliographic latitudes, while at sun-spot minimum the prominences are feeble and are confined to zones near the solar equator.

The streamers of the solar corona are best seen near the time of minimum of sun-spots. The splendid series of photographs secured by Lick Observatory expeditions have been utilized by Moore and Baker to measure the direction of the axis of symmetry of the polar streamers, photographs at five separate eclipses exhibiting the polar rays sufficiently well-determined for the purpose. The direction of the sun's equator is inclined about 7° to the ecliptic and 26°15′ to the terrestrial equator. The measures given in the following

[1] *Problems in Astrophysics*, 129, 1903.



General Spectrum of the Corona, June 8, 1918

Single prism, Lowell Observatory expedition. The strongest lines are due to the chromosphere and do not originate in the corona. Note that the bright lines stretch across the dark moon. These are caused by diffusion of the light of the chromosphere by clouds in the earth's atmosphere.

table show that the axis of symmetry of the polar rays coincides, within errors of measurement, with the rotation axis of the sun.

Axis of Symmetry of Polar Streamers in Solar Corona
(Position angles measured from North point of Sun)

Date of Eclipse	Axis of Polar Streamers			Rotation Axis	Polar Streamers minus Rotation Axis
	Moore	Baker	Mean		
1898 Jan. 21	9.4° W	9.3 W	9.4 W	8.2° W	1.2° W
1900 May 28	17.1 W	17.6 W	17.4 W	16.9 W	0.5 W
1901 May 18	21.5 W	20.7 W	21.1 W	20.3 W	0.8 W
1908 Jan. 3	0.9 W	0.8 E	0.0	1.2 E	1.2 W
1922 Sept. 21	24.4 E	24.8 E	24.6 E	25.0 E	0.4 W
				Average	0.8 W

How vacillating and uncertain have been the steps of progress in acquiring information of the spectrum of the corona! And how unsatisfactory that knowledge still is! The reasons are very patent: the coronal spectrum is very weak and the opportunities for investigating it are very few. All observers up to the eclipse of 1882 took it for granted that every spectral line seen at mid-totality, when to the eye there was no visible trace of the chromosphere, must perforce take its origin in the corona. It was with a great shock of surprise that H and K of calcium were seen in 1882 projected on the black face of the moon, where presumably there is no light at all. About thirty bright lines were photographed by Schuster and by Abney at the eclipses of 1882, 1883 and 1886. The wave-lengths at the three eclipses were in fairly good accord, but, to quote from the *Report of the Eclipse Committee, American section,* 1922, "It may be questioned whether any of the lines reported by them, except those near 4086 and 4232.8 A, were truly of coronal origin." Even as late as 1893, the H and K lines were assumed to belong to the corona. In Pringsheim's excellent book, *Physik der Sonne,* published in 1910, it is surprising to read the statement, on page 315, that hydrogen is found in the corona at a distance of 10′ from the sun.

Knowledge of the spectrum of the corona may almost be said to begin with the eclipse of 1893, when Fowler with a prismatic camera photographed nine rings, all of which agree in position with lines reported for the 1886 eclipse. At the same eclipse, Deslandres photographed three coronal lines at 3987, 4086 and 4231 A, and also three others at 3164, 3170 and 3237 A, in the ultra-violet. These last three have not been observed since by others, nor have two of Fowler's nine. It was not until 1898 that coronal spectra had acquired sufficient precision to distinguish between the chromospheric line 1474 K at wave-length 5317 and the "coronium" line fourteen angstroms farther to the violet, at 5303. Photographs were secured at the eclipse by Fowler, by Campbell, by Naegamwala, and by Newall and Hills. Additional photographs were secured by Frost in 1900, by Dyson in 1900, 1901 and 1905, by the U. S. Naval Observatory parties in 1900, 1901 and 1905, by Fowler and Lockyer in 1900, and by Lockyer and by Campbell in 1905. More recently the Lick expeditions have secured good photographs, by Lewis, and by Campbell and Albrecht in 1908, and by Lewis, by Campbell and Moore in 1918 and again in 1922.

At the eclipse of 1918, Slipher found on his photographs the green coronium line extending across the space occupied by the moon's image, — due to scattering of light in the earth's atmosphere. At the eclipse of August, 1914, Furuhjelm, using three-prism dispersion, secured eight coronal lines, five of which have not been observed elsewhere, and Carrasco, and Bosler and Block, independently discovered a new coronal line in the red, at wave-length 6374 A. In Lick *Observatory Bulletin, 10*, 1, 1918, Campbell and Moore give a summary of all of the reliable observations of coronal wave-lengths determined since the eclipse of 1893. The wave-lengths are given on Rowland's scale. The values, however, are still subject to great uncertainties, for even in the position of the strongest line of the spectrum, the green coronium line, large differences are found by the most skillful observers. The wave-length by Campbell and Moore of the Lick party is 5302.98 A, while Adams, St. John and Miss Ware of the Mt. Wilson expedition place the line farther

to the red, at 5303.20 A. Furuhjelm's value from the 1914 eclipse puts this line still farther to the red at 5303.36 A.

WAVE-LENGTHS OF CORONAL BRIGHT LINES

Wave-Lengths	Intensities	Wave-Lengths	Intensities
3164?		3986.9	Fairly strong
3170?		4086.0	Fairly strong
3237?		4130?	Faint
3288?	Faint	4231.4	Fairly strong
3328.2	Fairly strong	4241	Faint
3359	Faint	4244.8	Faint
3388	Very strong	4311	Faint
3455	Strong	4359	Rather faint
3461?	Faint	4398?	Very faint
3505?	Faint	4533.4	Faint
3534	Faint	4567	Rather faint
3601.3	Pretty strong	4586	Rather faint
3626	Faint	4722?	Faint
3641.4	Rather faint	4725?	Faint
3643.0	Rather faint	4779	Faint
3648	Rather faint	5073	Faint
3651?	Faint	5118	Faint
3801.0	Rather faint	5303.1	Very strong
3865?	Faint	5536	Faint
3891?	Faint	6374.2	Strong

Forty lines existing, or possibly existing, in the corona are given in the above table. The lines marked with (?) following the wave-length are weak lines measured by one observer only. There is consequently some doubt regarding their reality until they have been confirmed at future eclipses. Neither hydrogen nor calcium is found in the corona.

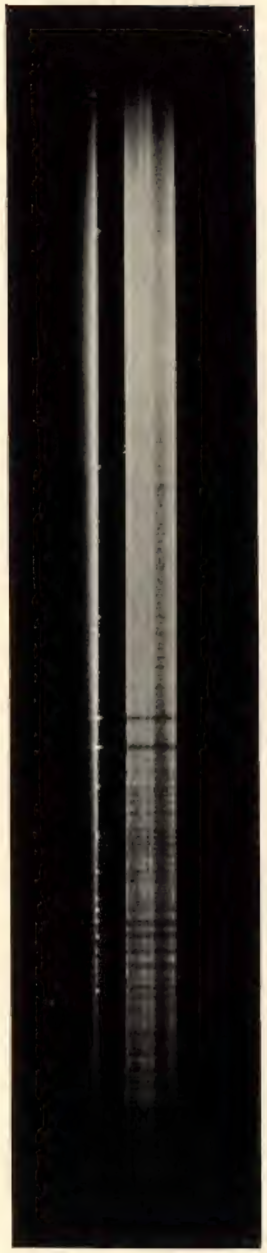
On account of the apparent simplicity of the spectrum of corona, Nicholson, in 1911, began a number of investigations of great value, the results of which have appeared in the *Monthly Notices of the Royal Astronomical Society*. An attempt was made by him to connect the wave-lengths by series relationships, and furthermore to find an explanation for these series on the hypothesis that the spectral lines took their origin in an atom consisting of a heavy nucleus

surrounded by negatively charged electrons. Nicholson's work was the first attempt to explain spectral series by means of Planck's quantum theory of radiation, according to which interchange of energy between systems of a periodic kind can only take place in certain definite amounts, or quanta, determined by the frequencies of the systems. A simple spectrum is shown also by the hypothetical element nebulium, the source of the prominent lines so well known in the spectra of nebulae. According to Nicholson,[1] the atom of nebulium contains four electrons, each with a negative charge *e*, rotating uniformly at equal distances in a circle round a positive nucleus whose charge is $4e$. When all four electrons are present, the atom is electrically neutral. If one electron is missing, the other three take up equidistant positions and rotate in a new orbit, the system then constituting an atom of nebulium with a single positive charge. The atom may lose a second electron, and then it will have a double positive charge. The neutral atom moreover may acquire an additional electron, or even two of them, when it will be singly or doubly negatively charged. By means of the principles of dynamics, Nicholson was able to represent the wave-lengths of the nebular lines with such a high degree of accuracy that the chance that the close agreement between theory and observation should be entirely fortuitous was estimated by him to be of the negligible size of 1 in 200,000.

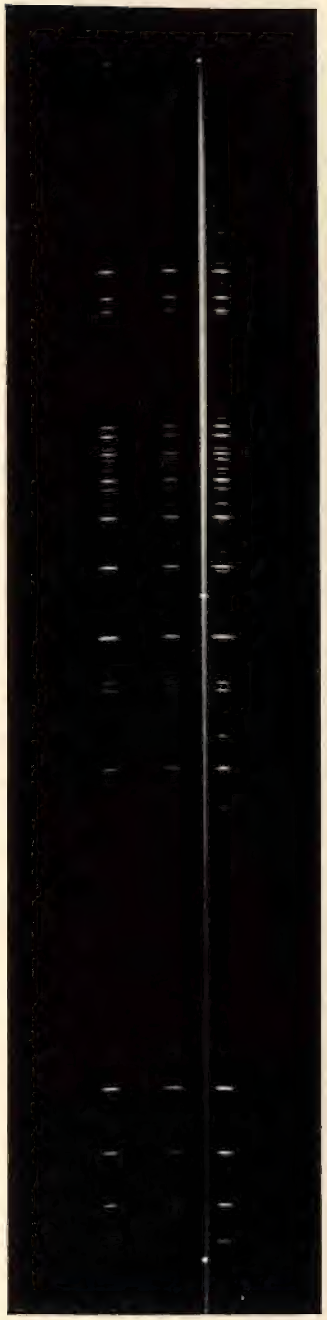
By a method similar to that followed in the case of nebulium, Nicholson found that most of the lines of the corona could be represented on the hypothesis that they are caused by electrons rotating around a nucleus with a positive charge $5e$. The name given to this hypothetical element is protofluorine.

The investigation of protofluorine failed to account for the prominent green line due to "coronium" at 5303 A and four others. When the line in the red at 6374 A was discovered at the eclipse of 1914, it too was unaccounted for by the hypothesis. In a further communication,[2] Nicholson

[1] *Monthly Notices, R. A. S.*, 72, 49, 1911.
[2] *Monthly Notices, R. A. S.*, 76, 415, 1916.



LICK PHOTOGRAPH, JUNE 8, 1918; SPECTRUM OF CORONA, WEST OF SUN (above) AND SOLAR SPECTRUM (below)



LICK PHOTOGRAPH, 1918, SPECTRUM FOR OBTAINING EXACT WAVE-LENGTH OF GREEN CORONIUM LINE WITH IRON COMPARISON SPECTRUM

shows that series relationships exist between the lines with wave-lengths 6374, 5303, 4567, 4359, 3643 and 3534, and that the wave-lengths are correctly represented on the assumption that coronium is a simple ring system with nuclear charge $7e$. These particular wave-lengths are given only when the coronium atom has annexed an eighth electron, and consequently, the atom is not electrically neutral but has an excess of a single negative charge.

Nicholson's atom has some points of resemblance with the Bohr atom, but differs from it in many essential details. Both types of atoms are concerned with negatively charged electrons rotating about a massive nucleus positively charged, and both are based on the quantum theory. The differences are found in the nature of the motions of the electrons. According to Bohr's theory, no light is emitted when an electron rotates in a stationary orbit but only when it jumps from one orbit to another; while according to Nicholson it is the rotation in the orbit that causes the emission. Both atoms represent equally well the simple case of the Balmer series for hydrogen. As already stated, the Bohr atom has been very successful in predicting other series due to hydrogen discovered by Lyman, by Paschen and by Brackett. Similar successes have not attended the Nicholson atom.

No terrestrial sources are yet known for the coronal and nebular lines. According to Nicholson's theory, the masses of the nuclei, or the atomic weights in the simple-ring systems, are proportional to the squares of the nuclear charges. Nebulium thence has an atomic weight of 1.31, protofluorine of 2.0 and coronium of 4.0, being therefore identical in value with helium. It is not an isotope of helium. It has been necessary for Nicholson to assume [1] that nebulium and the other hypothetical elements are "not strictly elements of the type found in the Periodic Table, but must be regarded as origins from which other elements may spring." This is a makeshift arrangement which recent investigations have not been able to corroborate. No place is left for these "origin-elements" in the periodic table

[1] *Monthly Notices, 74,* 486, 1914.

between hydrogen and helium, and they can have no real, or even transitory, existence. Bohr's atom and the ionization theory of Saha have probably brought us close to the discovery of the sources of the nebular and coronal lines. Pannekoek [1] has assumed that the coronal lines may be due to Ca^{++}. At present we know so little of the spectral lines which take their origin in the singly-enhanced, doubly- or triply-enhanced elements, that it is quite futile to guess which of the many possible elements will give the particular series of lines seen in the visible portion of the coronal spectrum. One guess is just about as good as another, — and therefore we shall refrain from hazarding a conjecture. The only possible method of securing real progress is to improve the observational data as much as possible. "The spectrum of the corona [2] at eclipses occurring at different phases of the sun-spot period should be photographed as expertly as possible with efficient instruments. The position of maximum intensity in the continuous spectrum of the corona should be determined at various distances out from the sun's limb, and be compared with spectrograms of other objects secured as nearly as possible under the same conditions, in order to estimate the effective temperatures of the coronal light sources, or possibly to secure indications as to the sizes of the particles in the coronal structure which diffuse the sun light falling upon them."

It is highly probable that the relative intensities of the emission lines of the corona vary with the sun-spot period, though information on this point is very meagre. It is difficult to compare spectra secured by different observers at different eclipses using instruments of vastly differing resolving powers, especially since the coronal lines are so weak and are seen projected on a background of continuous spectrum. Under these conditions, the intensities of the bright line spectrum secured with low dispersion instruments will obviously be less intense than for instruments of high dispersion.

[1] *B. A. N., 14,* 1922.
[2] *Report of Committee on Eclipses,* American Section, International Astronomical Union, 1922.

In addition to the bright line spectrum, the corona shows a continuous spectrum in the inner corona, 8′ or 10′ deep, with Fraunhofer absorption lines visible in the middle and outer corona. The early observations seemed to indicate that at sun-spot mimimum the green coronium line was weak and the Fraunhofer spectrum strong, while at sun-spot maximum the emission lines were stronger, and the dark lines weaker. It is only recently that observers have recognized that the presence of thin clouds at the time of the eclipse may greatly affect the visibility of the Fraunhofer lines observed in the corona. At the eclipse of 1901, photographed by Perrine in Sumatra through thin clouds, the coronal spectrum showed Fraunhofer lines in the region corresponding to the invisible moon! It is important, for testing various theories of the corona, that the distance out from the sun at which the absorption lines become invisible in the corona should be determined by adequate photographs taken under clear skies. The reason why the Fraunhofer lines are invisible in the inner corona within one-third of a diameter of the sun apparently seems to be a simple one, namely, that the lines are too weak to show there. A photograph of the flash spectrum taken in 1905 immediately after the end of totality showed the Fraunhofer lines only in the extreme ultra-violet and in regions of longer wave-lengths starting with the green. In the blue and violet portions where the photographic plate had greater sensitivity, the Fraunhofer lines undoubtedly existed, but they were too weak to show upon the strong continuous spectrum.

Various observers have investigated the rotation of the corona by measuring from spectra the Doppler effect of motion in the line of sight. It has been generally assumed that the corona rotates with the sun, which is at a rate of 2.0 km per second at the limb of the sun. A rotational speed of this size corresponds to a shift in wave-length of the coronium lines amounting to 0.035 A. And yet, the wave-lengths for this line in 1918 by the Lick and Mt. Wilson observers, each using an efficient instrument, differ by 0.2 A, or six times the rotational shift! It is probably no very great exaggeration to say that at the present time we

know absolutely nothing regarding the rotation of the corona. It is not impossible that the wave-lengths of the line 5303 may be determined with greatly increased accuracy, but, unfortunately, this line at best is faint, and the exposures available are very short. The best method of determining the rotational speed will be unquestionably by securing as accurate wave-lengths of this line as possible, with the slit of the spectrograph stretching across the sun's equator. If different values of wave-length are obtained for east and west limbs, thus indicating rotation, the observer should be very careful that he has eliminated all possible instrumental sources. In place of using the solar spectrum as a comparison, it is probable that more accurate wave-lengths will be obtained by using an artificial source, in the manner employed with stellar spectra. The comparison spectrum could readily be superposed on the black moon.

In spite of the pitifully small amount of time available for the investigation of the spectrum of the corona, much knowledge has been acquired; but, unfortunately, suspicion has also been cast on some of the information we thought was fully secured. A brief summary of what we now *think* we know may not be out of place. Three types of spectra must be distinguished: the continuous spectrum close to the edge of the sun, the emission spectrum, and the Fraunhofer spectrum. The coronal spectrum is now fully distinguished from that of the chromosphere. The lines of calcium and hydrogen, frequently photographed at mid-totality, do not belong to the corona, but are caused by the light of the chromosphere being diffused in the earth's atmosphere, usually by thin clouds. The coronal lines have been arranged in series by Nicholson. The combined attack now being made on the atom, by the astronomer, the physicist and the chemist, will probably reveal before long the nature of the particular kind of atom that gives origin to lines of coronium, protofluorine and nebulium. It is true that there are only 92 places in the Periodic Table that can be occupied by elements, but this does not necessarily mean that there are only 92 different kinds of atoms. Far from it! When we remember that the neutral atom gives its

characteristic spectrum, which differs from the spectrum of the same element ionized by losing one, two, three or more electrons, we see there are possibly as many as three hundred different kinds of atoms, each of which gives its own particular spectrum. In addition, there are isotopes indistinguishable spectroscopically from other atoms. We are sure that none of the elements in the lower half of the periodic table can be the hypothetical coronium, but which one is the mythical element in the upper half, or third, or probably upper quarter of the table it is hard to conjecture. Helium baffled the scientist for a quarter of a century before it revealed its secret. Coronium was recognized over half a century ago, but in this long interval about one hour only has been available for observational investigation of it.

It is very important to know whether the Fraunhofer lines seen and photographed at several eclipses in the past half century actually exist in the corona or are caused merely by haze or clouds in the earth's atmosphere. If these dark lines take their origin in the coronal spectrum it is important to see whether their intensity and also that of the bright-line spectrum vary with the sun-spot phase. Many observers have found that the spectrum of the sun is much richer in ultra-violet light than the continuous spectrum of the corona. The shift in maximum of intensity to the red signifies that the corona is at a cooler temperature than the photosphere. There is evidently much to be learned about the coronal spectrum, but its secrets will be bared only by the use of efficient spectrographs in the hands of capable and experienced observers.

A great increase in our knowledge of the coronal spectrum came as the result of the observations of the Lick Observatory [1] at the Australian eclipse of September 21, 1922. On account of the perfect weather conditions and long duration of totality an opportunity was afforded for carrying out an extensive program.

On account of the uncertainties still existing in the value of the wave-length of the green coronium line, photographs were secured with large dispersion. A plane grating was

[1] Moore, *Publ. A. S. P.*, *35*, 59, 1923.

used of 15,000 lines to the inch with a collimator of 60 inches focus, with the slit placed across the sun's equatorial diameter, and an attempt was made to photograph not only the green line, but the red line at 6374 A as well. No trace was found of the latter line and the green was recorded very faintly and on one side only, the eastern edge of the sun.

With a smaller dispersion of a single prism and collimator of 21 inches focus, two exposures were made of 46 seconds and 4 minutes 14 seconds, respectively. The shorter exposure recorded the brighter coronal lines, the continuous spectrum of the inner corona and a faint discontinuous spectrum of the outer corona visible to 15′ from the sun's edge. The longer exposure exhibited the absorption spectrum of the outer corona to an angular distance of 35′ from the limb of the sun. In order particularly to test the character of the spectrum given by the outer corona, a still smaller dispersion of a single prism and collimator of 12 inches focal length was employed. The slit of this instrument was made sufficiently long to include some of the sky background and an exposure of 5 minutes and 9 seconds was given. The purpose was to see if any traces of Fraunhofer lines were found in the sky spectrum caused by possible thin haze in the terrestrial atmosphere.

The spectra taken with each of the instruments of one-prism dispersion exhibited the continuous spectrum and most of the bright lines confined to a region 4′ to 6′ from the sun's limb. The maximum was found for the green line with an extension of 8′ from the edge of the sun. The spectrum of the outer corona seemed unquestionably to show the Fraunhofer lines which were specially visible to the violet of $H\gamma$ where the continuous spectrum was less intense. No trace of the sky spectrum was found to exist beyond the limits of the coronal spectrum. Since the sky was remarkably clear, without the slightest evidence of haze or clouds, it is manifest that the Fraunhofer lines of the 1922 eclipse did not take their origin by reflection in the earth's atmosphere. Moore's observations in thus proving the Fraunhofer lines of the outer corona are caused by the scattering of the sun's light by the atoms of the corona

are of the utmost importance in advancing our knowledge of the perplexing solar aureole.

The spectra secured with the slit spectrographs and also by means of an instrument without slit seemed to prove conclusively that the coronal emission lines in 1922 were much fainter than those of the eclipse of 1918, also obtained by the Lick-Crocker expedition. The corona of 1922 was of the sun-spot minimum type. Hence, the suspicions of previous observers that the bright lines of the corona are fainter at sun-spot minimum than they are at sun-spot maximum seem to be completely confirmed.

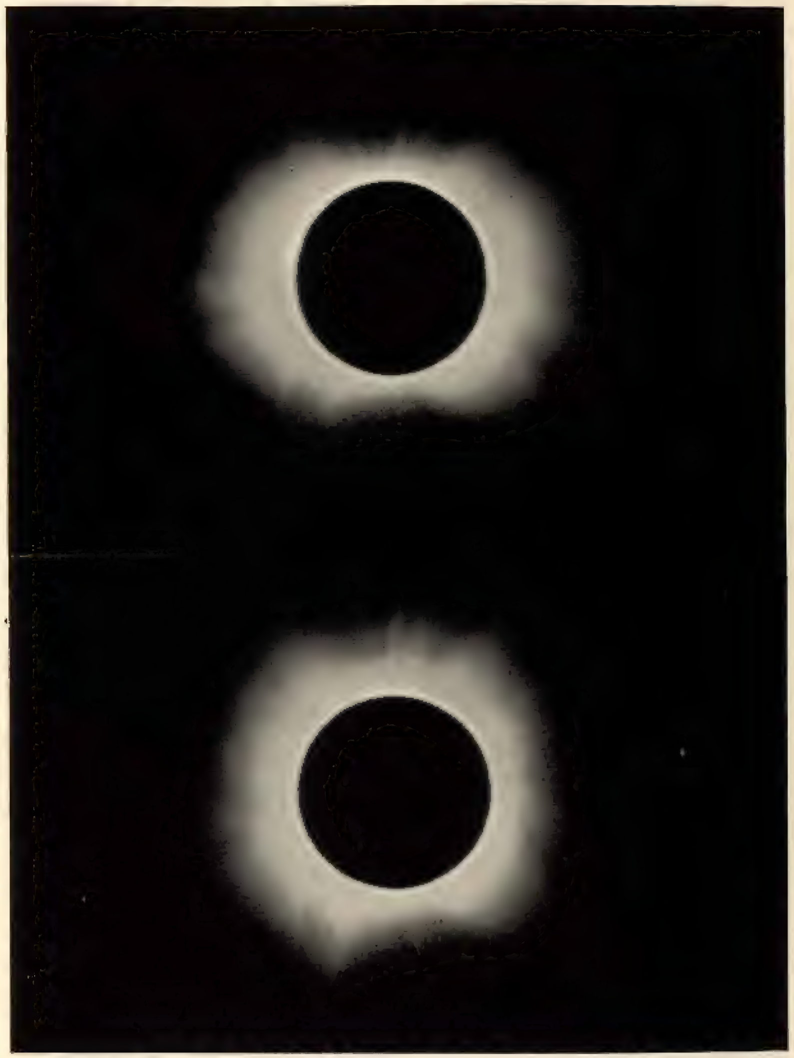
CHAPTER XIX

CORONAL THEORIES

IF THE Fraunhofer lines are actually found in the spectrum of the corona, they must be caused by the reflection of chromospheric light by matter existing in the corona in a finely-divided state. Fortunately, there are methods available for testing the question of scattering in the corona, namely, by observations for the determination of the polarization of light. Since the eclipse of 1860,[1] when Secchi and Prazmowski first took up the subject, polarization observations have found their place at almost every total eclipse. At the beginning of the investigations, they were carried out entirely by visual methods; but in a manner similar to what has happened in other branches of astronomical work, photographic observations have gradually displaced visual ones, and as a consequence greater and greater precision has been attained. The accurate determination of the percentage of polarized light has an important bearing on the study of the distribution of matter in the corona. To be of the greatest value, the polarization should be known for different distances from the sun's limb.

In general, there are two different methods of analyzing polarization; one is by the use of double-image prisms, the other by means of plane mirrors. There are many variations of these methods possible. In 1900, Wood employed a direct vision prism before the object-glass of a telescope, the eye-piece containing a Savart plate and a Nicol prism. This combination gave a continuous spectrum crossed by very distinct diagonal interference bands, manifesting fairly strong polarization estimated to equal between 10 and 15 percent. The character of the interference bands indicated that the bright-line spectrum was not polarized, or in other

[1] *Comptes Rendus, 51,* 195, 1860.



THE CORONA PHOTOGRAPHED WITH POLARIZED LIGHT. LICK OBSERVATORY EXPEDITION, JANUARY 3, 1908

Note the difference in the distribution of coronal light in the two photographs.

words, that the light causing these lines was not reflected sunlight. The appearance presented in the telescope however differed so materially[1] from what had been expected that it took many of the precious seconds of totality for the observer to readjust his ideas; and all the while he could not help but feel that something radically wrong must have happened to the apparatus. At the same eclipse, Dorsey[2] photographed the corona through a double-image prism in the manner utilized by A. W. Wright in 1878. The method gives two photographs of the corona on each plate; one having cut out of it all the light polarized along the line joining the two images, and the other all that polarized at right angles to this direction. Hence, if the corona is polarized radially or tangentially, one image will be deficient in light along the diameter perpendicular to this direction. Which image is deficient along the line joining the centers of the two photographic images depends on the kind of double-image prism used and whether the polarization is radial or tangential. Dorsey also examined the corona visually by a polarimeter consisting of a telescope in the focal plane of which was placed a biquartz half an inch square. The eye-piece contained a Nicol prism, and between the objective and the biquartz was a double pile of plates. The conclusions were that the corona is polarized radially, the visual observations giving the amount of eleven percent at a distance of 8′ from the moon's limb, a value agreeing well with Wright's 11.2 percent found at 7′ from the moon's limb at the eclipse of 1878.

No attempt can be made to give here a complete account of the numerous observations made at various eclipses to determine the amount of polarization. Special mention, however, should be made of the excellent work by Newall and by Turner, each of whom has observed polarization effects at several eclipses. In *Lick Observatory Bulletin, 6,* 166, 1911, R. K. Young discusses the measures of photographs secured by Perrine of the Lick Observatory at eclipses of 1901, 1905 and 1908. At the Sumatra eclipse,

[1] *Publications of the U. S. Naval Observatory, 4,* D 116, 1905.
[2] *Publications of the U. S. Naval Observatory, 4,* D 117, 1905.

the plates were secured by a double-image camera with the prism set in succession at five different positions separated by angles of a quarter of a right angle At the two succeeding eclipses, photographs were secured by the same double-image camera and also by a reflecting polarigraph. This latter consisted of three cameras with lenses of three inches aperture and fifty inches focal length. In front of each of two of the lenses was placed a glass reflector, so inclined that the light from the corona was incident at the polarizing angle, the planes of polarization of the two reflectors being perpendicular to each other. The third camera was used merely as a check. The measures showed that the polarization was radial and that the percentage of observed light increased rapidly from the limb, reaching a maximum of thirty-seven percent at 5′ distance, and then diminished slowly, being thirty-five percent at 9′ from the limb. Assuming the well-known law of the reflection and scattering of light that it varies inversely as the fourth power of the wave-length, the value of 11 percent in the visual region 5600 A would correspond to 33 percent in the photographic region 4270 A. A close accord is thus seen to exist between the visual values obtained from the eclipses before 1901, and the photographic results from the three eclipses of 1901, 1905 and 1908. In view of the very great difference between the amounts of polarization in the visual and photographic regions, it is highly desirable that values in the visual region be obtained by photographic methods by the use of a color filter and isochromatic plates. In view of the experience of Wood at the eclipse of 1900, it is urged that all observations in the future for polarization effects be made photographically. Observations might possibly still be made visually by experienced observers, but such values should be looked upon merely as checks on the more accurate photographic results. Observers should be most careful to know the amount of polarization caused by the apparatus itself so as to eliminate these effects from the total polarization observed during the progress of the total eclipse. As is well known,[1] every

[1] Wood, *Astrophysical Journal*, *12*, 283, 1900.

form of apparatus that disperses light, at the same time polarizes it. A Rowland grating gives strongly polarized spectra; and with prismatic spectra, as the dispersion is increased by additional prisms, the polarization is likewise increased by the new surfaces added.

At the eclipse of 1918, Lewis of the Lick Observatory party, by means of two separate double-image cameras, secured successful photographs in two different regions of the spectrum by using blue and green color filters. The effect for the blue was found to be greater than for the green. Quantitative values for the amount of polarization could not be furnished however for two reasons: first, the law of diminution of the intensity of coronal radiation at different distances out from the moon's limb is unknown; and second, the effect on the corona, of polarization of the light of the sky surrounding the corona, has not been fully investigated. At the eclipse of 1905, Newall[1] found that at a distance of three-quarters of a degree from the center of the corona, the strength of the Savart bands from the sky neutralized those from the corona. This signifies that from the veil of the illuminated sky between the observer and the corona there came as much polarized light as from the corona three-quarters of a degree from the center. Unquestionably, the character and intensity of the atmospheric polarization vary considerably at different eclipses, which of necessity are observed under different conditions of clouds and moisture in the terrestrial atmosphere. On account of the great intensity of the corona close to the sun, for instance, at 1′ from the limb, it is difficult to measure the intensity of the darkening of the photographs and hence to evaluate the amount of polarization so close to the edge of the sun. Newall in 1901 obtained "quite marked polarization" at 1′ from the limb. The Savart photographs for testing polarization seem to possess some advantages over the double-image or reflection methods (see Newall, *loc. cit.*).

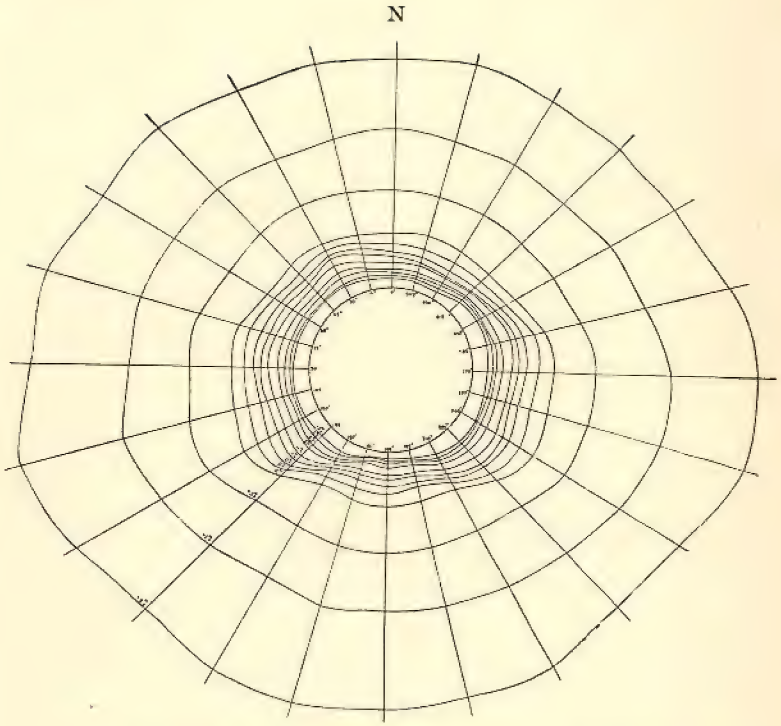
The only means of unravelling some of these puzzles seems to lie in determining the law of change in the intensity of the corona at different distances out from the limb of

[1] *Monthly Notices, R. A. S.*, *66*, 475, 1906.

the sun. The law best known is that of Turner,[1] as the result of photographs obtained in 1898, that the intensity of the corona varies from the edge of the sun outwards inversely as the sixth power of the distance measured from the center of the sun. At the eclipse of 1905, Schwarzschild[2] confirmed Turner's law, and this same eclipse, Graff[3] assumed the correctness of this law to determine the law of blackening of his photographic plates. But at this same eclipse of 1905, Becker[4] found the intensity of the corona subject to a different law, that it varied inversely as the fourth power of the distance counted from a point one-seventh of a solar radius inside the edge of the sun. At the eclipse of 1908 by means of measures carried out by the bolometer, Abbot[5] confirmed Becker's law rather than that of Turner, while R. K. Young (*loc. cit.*) found an intensity depending on the inverse sixth and eighth powers of the distance measured from the center of the sun.

A very different law was found by Bergstrand in a very important publication entitled "Études sur la distribution de la lumière dans la couronne solaire," Upsala, 1919. From photographs secured at the eclipse of August 21, 1914, an attempt was made to determine the relative intensity of light distributed within the corona. The measurement of the absolute intensity and the estimation of the total light of the corona, compared for instance with that of the full moon, did not form part of the program. The problem is one of photometry, and for its solution can be brought the vast experience gained by many years of investigation in determining the magnitudes of the stars. Of the several methods available, Bergstrand adopted the plan of employing twin photographic objectives, mounted equatorially in such a manner that the two solar images could be impressed upon one and the same photographic plate. On the day of the eclipse the times of exposure of the two objectives were

[1] *Popular Astronomy, 14,* 548, 1906.
[2] *Astron. Mitteil. zu Gottingen, 13,* 1906.
[3] *Astron. Abhandl. der Hamburger Sternw. in Bergedorf, 3,* 1, 1913.
[4] *Memoirs, R. A. S., 57* and *Phil. Trans. Roy. Soc. 207 A,* 1908.
[5] *The Sun,* 133, 1911.



Curves Showing Intensity of Light in Corona, August 21, 1914
Measures by Bergstrand in units of stellar magnitude.

made identical, but the aperture of one of the objectives was reduced by means of a suitable diaphragm to one-third that of the other.

The intensity of the silver deposit measured on the plates is the summation of two separate effects, one of which is due to the corona itself while the other comes from the diffuse light of the sky. Added to these two, there is in reality a third effect found close to the moon's limb, that of a halo caused by reflection from the glass-side of the plate of the strong illumination of the inner corona. Fortunately, the intensity of the corona could be separated from the two other effects. The values thus secured do not in any manner confirm Turner's law of the inverse sixth power nor yet the law of Becker according to which the intensity varies inversely proportional to the fourth power. In fact, Bergstrand finds that the intensities near the solar equator differ greatly from those near the poles, the equatorial rays having an intensity three times as great as the polar rays. The equatorial and polar intensities, however, can be brought into relationship with each other in a very simple manner by supposing that the corona is composed of two phenomena. One of them, the " interior corona " exists exclusively in the equatorial zone. In both of these phenomena, the intensity of the light is inversely proportional to the square of the distance measured from the edge of the sun, the intensity of the " equatorial corona " being, however, about double that of the " interior corona." On page 342 is given a curve representing Bergstrand's values. Measures were carried out on solar radii separated from each other by 15°. Position angles are designated from the north towards the east. The intensity at a distance of one radius from the edge of the sun is taken as unity, and values are represented in terms of stellar magnitudes, where a difference of five magnitudes represents a change of a hundred-fold intensity. The strongest coronal rays at times depart sensibly from the direction of the solar radius. This is shown by a jet which leaves the sun at position angle 25° but which does not go out radially and is found in the external curves between 30° and 45°. Some of the most intense rays apparently

do not take their origin from the edge of the sun but rather from the front or back side of the solar disk. Moreover, the structure of the corona is highly complicated, since the distribution of jets is not uniformly distributed in all longitudes and since they frequently depart sensibly from the radial direction. On account of the greater strength of the equatorial rays, it was possible for Bergstrand to observe these rays on the photographic plates to a distance of ten radii, or five solar diameters from the edge of the sun, before they diminish in intensity to that of the diffuse sky light. In the polar direction, equality was attained at a distance of three and a half solar diameters.

An excellent form of instrument for measuring the intensity of the corona as depicted on photographic plates is the registering photo-micrometer.

It is evident that our knowledge regarding the distribution of light within the corona is in a very unsatisfactory state, since the law of the intensity has been found to be inversely as the second, fourth, sixth or even eighth power of the distance from the sun. It is consequently of great importance that a well-devised form of apparatus be constructed for use at eclipses, and that photographs be secured both in the violet and visual regions on a carefully prepared plan at several future eclipses. The apparatus used by Bergstrand seems to leave little room for improvement. If the photographic plates secured at the eclipse could be impressed by light from a standard source, and if in addition photographs of the full moon were obtained, we should then be in a position of having information additional to that acquired during the progress of an eclipse. We need to know whether the intensity of the distribution of light within the corona follows the same law at every eclipse, or whether this law varies according to the sun-spot period, and we need to know the law both in the blue and yellow regions. We shall naturally expect to find that the relative intensity of the "interior corona" of Bergstrand compared with the "equatorial corona" will be greatly different at sun-spot maximum and sun-spot minimum. Not until we secure more reliable information on these questions,

and in addition carry out a well-standardized series of observations to determine polarization at several eclipses, can we expect to advance much in the solution of the coronal problems.

Before taking up the various coronal theories, it will be well to consider the measurements made for determining the *total* light of the corona. It will not be necessary here to go into a detailed discussion, since this has been done by Kunz and Stebbins.[1] Omitting one unreliable value made in 1900, the following table is copied from their summary. The total light of the corona is expressed in terms of the total light from the full moon.

TOTAL LIGHT OF THE CORONA

Eclipse	Method	Observer	In terms of full moon
1886	Photographic	W. H. Pickering	0.025
1889, January	"	Holden	0.04
1889, December	"	Holden	0.02
1893	"	Turner	0.6
1898	"	Turner	1.1
1898	"	Bacon and Gare	2.7
1905	"	Graff	0.26
1905	"	Schwarzschild	0.17
1908	"	Perrine	0.11
1886	Visual	Abney and Thorpe	0.8
1889, January	"	Leuschner	0.4
1893	"	Abney and Thorpe	1.1
1905	"	Fabry	0.75
1905	"	Knopf	0.85
1918	Photo-Electric	Kunz and Stebbins	0.50

The photographic determinations at the eclipse of 1886 and the two eclipses in 1889 give values that are apparently too small. The direct mean of the other twelve determinations shows the total light of the corona to possess 79 percent of the light of the full moon. The inclusion of the three values, each with half weight, diminishes the value of the coronal light to 70 percent of the moon. Kunz and Stebbins observed the 1918 eclipse with a potassium photo-

[1] *Astrophysical Journal*, 49, 137, 1919.

electric cell. They compared the light of the corona with a standard candle, with two electric lamps, with the full moon, and with an area of the sky during totality and during full sunshine. Their numerical results are as follows:

Observed total light of the corona	0.60	candle-meters
Same, corrected to outside of atmosphere	1.07	candle-meters
Observed ratio of corona to full moon	0.6	
Same, corrected to outside of atmosphere	0.50	
Observed ratio of corona to sky circle of diameter one-half degree and 8° from uneclipsed sun	0.105	
Same during totality	640.	

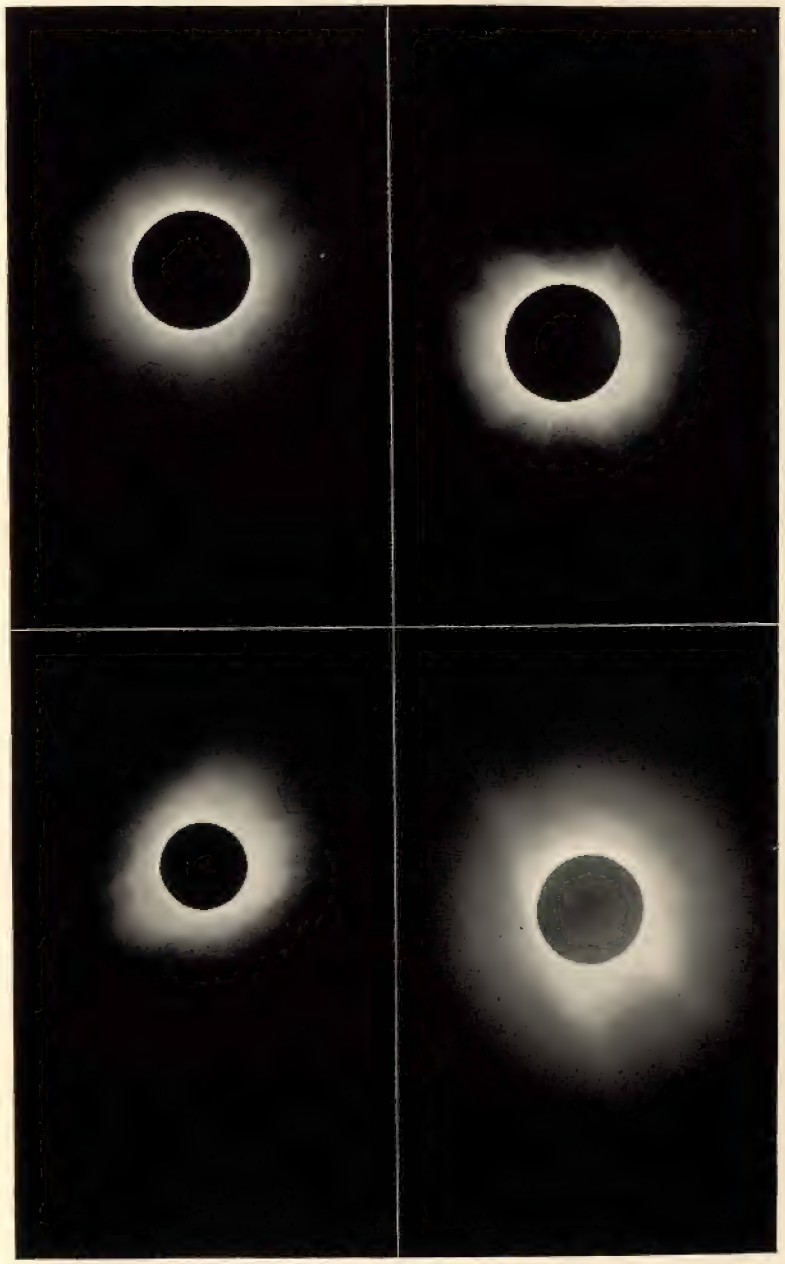
The photo-electric cell with which these measures were secured had a maximum sensibility at wave-length 4500 A in the blue.

At the eclipse of 1908, Abbot secured valuable measures with the bolometer, and a summary is given below of the values at Flint Island:

Sun near zenith	10,000,000
Sky 20° from uneclipsed sun	140
Sky average	62
Corona at 1′.5 from limb	13
Corona at 4′ from limb	4
Moon about 50° zenith distance	12 (?)

It appears, therefore, from the above values that the corona of 1908 equalled the moon in radiation transmissible by glass only in the brightest parts of the inner corona. Abbot's values make the moon about one-tenth the brightness of the sky at 20° distance from the sun, while according to Kunz and Stebbins the moon is one-tenth the brightness of the sky at 8° from the sun. The conclusions to be drawn from this conflicting testimony may be either that the moon is relatively richer in blue light than in the infra-red, or else that one or the other, or both sets of measures are in error.

It is obvious that the total light measured by Kunz and Stebbins in 1918 included the light from the prominences which were unusually brilliant at this eclipse. What portion of the whole light was due to these prominences it is naturally impossible to tell.



1905 Spain

1908 Flint Island Pacific

1918 America

1922 Australia

THREE CORONAS PHOTOGRAPHED BY LICK ASTRONOMERS AND ONE (1922) BY CANADIAN OBSERVERS

At the eclipse of 1918, Aldrich[1] found that the total brightness of the sky during totality was less than that of twilight one hour after sunset of the same day. At the Australian eclipse of 1922, Ross directed a camera, from which the lenses had been removed, towards the south celestial pole and exposed a photographic plate during totality. Other plates from the same box were exposed on the evening of the same day for equal intervals of time at 6:14, 6:17, 6:20, 6:23 and 6:26 by the clock. The central portions of the plate were cut out and all six plates were developed together. The plates showed a regular gradation. It was found that the illumination at the south celestial pole corresponded with that when the sun's center was 97° 29′ from the zenith.

When we attempt to solve the enigma of the corona, we are face to face with one of the most difficult problems in the whole realm of astronomy. Very positive decisions can be given regarding what it is *not*.

First of all, the corona is not an atmosphere of the sort generally signified by this word. The atmosphere of the earth consists of a number of gases, of which oxygen and nitrogen are the most important. Observations of meteors show that this atmosphere extends more than a hundred miles upwards above sea-level, while traces of auroral displays have been detected to altitudes of four hundred miles. The molecules of gas forming atmospheric air are attracted to the earth by gravitation with the result that there is a pressure at sea-level of fifteen pounds per square inch, this being caused by the weight of the column of air. But gravity on the sun is 27 times more powerful than the value on the earth, while the corona has been observed to the enormous distance of ten million miles from the surface of the sun. Thus it is easy to see that if the corona were truly atmospheric in its nature, the resulting pressure at the surface of the sun would be simply colossal, — and we are absolutely positive that such enormous pressures do not exist there. The chromosphere is indeed the solar atmosphere, not one of oxygen and nitrogen as on the earth, but of the

[1] *Smithsonian Miscellaneous Collections, 69,* No. 9, 1919.

gases found to exist in the flash spectrum, each heated to high temperatures due to their proximity to the sun.

In the forceful words of Simon Newcomb[1] we may remind the reader that "the great comet of 1843 passed within three or four minutes of the surface of the sun, and therefore directly through the midst of the corona. At the time of nearest approach its velocity was 350 miles per second, and it went with nearly this velocity through at least 300,000 miles of corona, coming out without having suffered any visible damage or retardation. To form an idea of what would have become of it had it encountered the rarest conceivable atmosphere, we have only to reflect that shooting stars are instantly and completely vaporized by the heat caused by their encounter with our atmosphere at heights of from 50 to 100 miles; that is, at a height where the atmosphere entirely ceases to reflect the light of the sun. The velocity of shooting stars is from 20 to 40 miles per second. Remembering, now, that resistance and heat increase at least as the square of the velocity, what would be the fate of a body, or a collection of bodies like a comet, passing through several hundred thousand miles of the rarest atmosphere at a rate of over 300 miles a second? And how rare must such an atmosphere be, when the comet passes not only without destruction, but without losing any sensible velocity? Certainly so rare as to be entirely invisible, and incapable of producing any physical effect." Other comets, the great comet of 1882 for instance, have almost grazed the sun's surface.

Any adequate theory of the corona must be capable of explaining[2] the following facts:

1. Its spectrum shows the bright emission lines of coronium.

2. Its spectrum shows also continuous light in the inner corona, and Fraunhofer lines in the middle and outer corona.

3. The emission lines of the spectrum are fainter at minimum of spots than at maximum.

[1] *Popular Astronomy*, 265, sixth edition, 1887.
[2] See also Abbot, *Smithsonian Misc. Collections*, *52* 31, 1908, and *Lick Observatory Bulletin*, *5*, 15, 1908.

4. The total brightness of the corona is very small.

5. Polarization is a maximum at a distance of about 5′ from the sun's limb, and it diminishes more rapidly towards the sun than away from it.

6. Matter of any kind so close to the sun must be very hot and must reflect and scatter the solar rays.

7. According to the observations of Abbot, the coronal materials are deficient in heat rays.

8. If the sizes of the coronal particles change in diameter at different distances from the sun's limb a corresponding change in color of the corona would result. No change in color is noticeable.

9. The internal motions in the corona are very small.

10. The sun exhibits a magnetic field.

11. According to Bergstrand, the intensity of the corona varies inversely as the square of the distances from the sun's surface.

12. It is necessary to explain the changing form of the corona with variation in the sun-spot period.

The first theory of the corona to be propounded was the one, so very popular at the time and thought to be capable of explaining away most of the astronomical problems, — the meteoric hypothesis. In virtue of this theory, the corona is nothing more nor less than the trails of myriads of meteors as they fall into the sun. Even at the time[1] a great authority on meteors, Newton of Yale, pointed out that the details observed in the corona were "inconsistent with any conceivable arrangement of meteoroids in the vicinity of the sun." The hypothesis was such an artificial one and had so little to commend itself that it is surprising that it found such a large place in astronomical literature, — but then we must not forget that very little was known concerning the corona.

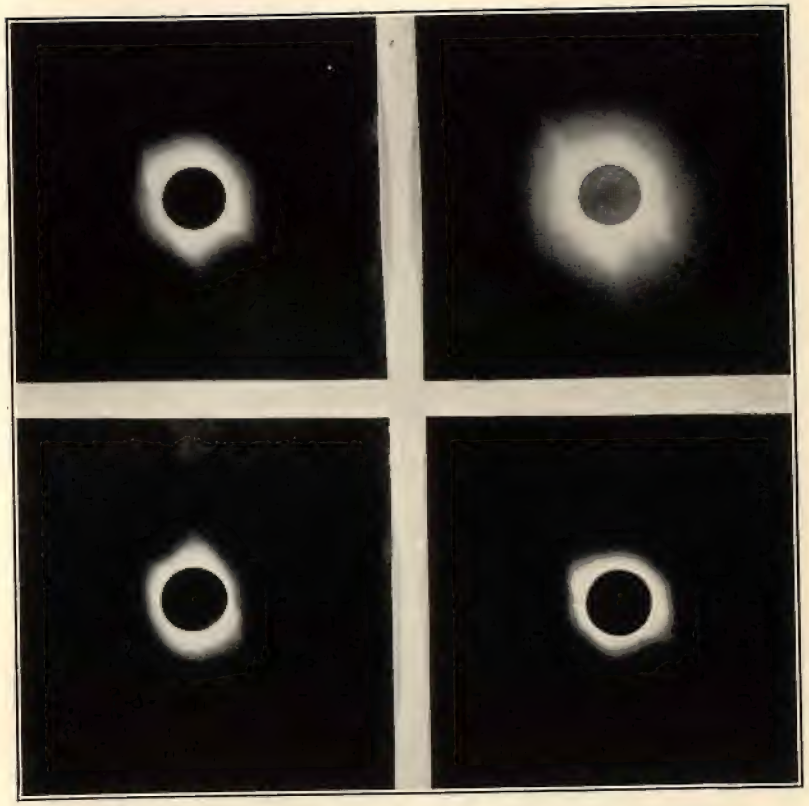
Schaeberle's mechanical theory of the corona has much more to recommend it, — but it too does not seem to have been able to bear the test of time, at least not in its original form. By virtue of this theory, the corona is caused by light emitted and reflected from streams of matter ejected

[1] *Nature*, Sept. 30, 1866.

from the sun by forces acting along lines normal to the surface of the sun. The forces are most active near the center of the sun-spot zones, and consequently, are confined almost wholly to the equatorial regions. Hence, as a result of this theory, the rays seen around the poles of the sun can have no existence, except that of streamers from the equatorial regions seen projected by perspective above and below the poles. In order that the force of ejection may be sufficiently great to overcome the attraction of gravitation, it was necessary to ascribe to the materials forming the longest rays initial velocities as large as 400 miles per second. While velocities of this size are not impossible on the sun, the truth of the matter is that no such motions have ever been discovered in the corona. Hence it is necessary to discard the theory or to modify it in some essential details. Moreover, "according as the observer is above, below, or in the plane of the sun's equator, the perspective overlapping and interlacing of the streamers cause the apparent variations in the type of the corona." This explanation might satisfy an annual variation (which is not known to exist), but fails to account for the change in form coincident with the eleven-year sun-spot period.

There are, unquestionably, many forces acting on the coronal materials repelling the particles away from the sun in opposition to gravitation, and as these forces have been considered one by one, different coronal theories have been propounded. In 1885 the "electrical theory" was enounced by Huggins.[1] The eclipse of 1889, of the minimum sun-spot type, having exhibited strong polar rays much resembling the lines of force about a magnet, Bigelow[2] brought forward the "magnetic theory," and Ebert[3] the "electro-magnetic theory." Bigelow's theory is very successful in explaining the details of the minimum type, but not so fortunate with the other forms of corona. The recent investigations at Mt. Wilson have shown that a magnetic field does exist around the sun, as demanded by Bigelow's theory.

[1] *Proc. Royal Society, 39,* 108, 1885.
[2] *The Solar Corona discussed by Spherical Harmonics,* 1889.
[3] *Astronomy and Astrophysics, 12,* 804, 1893.



CANADIAN PHOTOGRAPHS, AUSTRALIA, SEPTEMBER 21, 1922
Upper pair: exposures 10 sec. (left) and 20 sec. (right).
Lower pair: through Nicol prism turned 90° between exposures, each of 5 sec.

Great have been the claims of the exponents of the " radiation-pressure theory " not only for explaining the details of the corona, but also for furnishing a rational elucidation of why comets' tails always point away from the sun, and what causes the aurora borealis, zodiacal light, etc. That a ray of light exerts a pressure on any surface on which it impinges comes as a direct result of the Electro-magnetic Theory of Light published in 1873 by Clerk Maxwell,[1] and as was shown by Bartoli [2] in 1876, can be deduced from the second law of thermodynamics. The pressure of sunlight at the surface of the earth, Maxwell computed from the known constants of solar radiation to be 0.592×10^{-10} grams per sq. cm. (This value is changed somewhat by using the latest determination of the solar constant as derived by Abbot.) At the sun's surface, as was pointed out by Arrhenius,[3] the radiation is much more powerful, and amounts to 2.75×10^{-3} grams per sq. cm. If then, we imagine at the sun's surface a cubical block of water of 1 cm edge, the pressure of light on it would be one ten-thousandth part of its weight, since superficial gravity at the sun is 27.47 times what it is on the earth's surface. If we decrease the size of the water particle, the pressure diminishes as the square of the edge and the weight as the cube. Consequently, for a little cube of water with an edge 10^{-4} cm, i.e., one micron, or μ, the pressure of the sun's light on it is exactly equal to its weight, and for a smaller cube of water the pressure would be greater than the weight, and the particle would be repelled just as if gravity had become negative. If the drop of water were spherical in shape instead of cubical, the critical diameter, at which the repulsion due to light-pressure would be equal to the attraction of gravity, would be $1.5\ \mu$. For other substances, the diameter is inversely proportional to the specific gravity.

The vapors of comets, as we are informed by the spectroscope, appear to consist largely of hydrocarbons with a specific gravity about 0.8, and for these the critical diameter

[1] *Electricity and Magnetism*, 792.
[2] *Il Nuovo Cimento, 15*, 195, 1883.
[3] *Physikalische Zeitschrift, 2*, 81, 1900; also, *Lehrbuch der kosmischen Physik*, 150, 1903.

would be about 1.9 μ. If the vaporized portions of the comet form drops whose diameters are greater than this value, a tail will be formed pointing toward the sun; but if the diameters are less than 1.9 μ, the tail will point away from the sun. If it should happen that drops of different sizes are formed — and there seems to be no reason why this should not be possible — the comet will have several tails, as in the comet of 1744 which had five.

Such, in brief, is the theory of Arrhenius, which readily enough explains away a great many of the difficulties connected with comets and their tails.

Since the light-pressure depends directly on the intensity of the sun's radiation, which decreases inversely as the square of the distance, as is also the case with gravity, the ratio of pressure to weight is therefore a constant independent of the distance from the sun. The manner in which this ratio is found was first shown by Bessel[1] in 1836, who computed the magnitude of the repulsive force from the curvature of the tail of the comet of 1811. Bredichin[2] more recently, from measures of many comets' tails, has found them to be of four different types, in which the repulsive forces are respectively 18.5, 3.2, 2.0, and 1.5 times the attraction of gravity; the straight tail, according to his ideas, consisting of hydrogen, the plume-like tail of hydrocarbons, and the short stubby one of metallic vapors, chief among which are iron and sodium. The electrical force, on which Bredichin explains his repulsions, has been shown by Lebedew[3] not to have a sound physical basis.

This objection cannot be raised to the principle of Arrhenius. That light actually exerts a pressure has been shown by Lebedew,[4] and Nichols and Hull[5]; the latter, indeed, have succeeded[6] in producing a laboratory comet's tail, although, as pointed out by them, other forces than light-pressure probably helped to give the repulsion.

[1] *A. N., 13*, 185, 1836.
[2] *Annales de l'Observatoire de Moscou*, (2)1, 45, 1886.
[3] *Astrophysical Journal, 16*, 155, 1902.
[4] *Annalen der Physik*, (4) 6, 433, 1901; *Astrophysical Journal, 15*, 60, 1902.
[5] *Physical Review, 13*, 307, 1901; *Astrophysical Journal, 15*, 62, 1902.
[6] *Astrophysical Journal, 17*, 352, 1903.

However, a rigid application of the theory of Maxwell is possible only when the body acted upon is large compared with the vibrations of light itself. When the body is of a size approximating the wave-length of light, Schwarzschild[1] has shown that the maximum value of the repulsive force is about twenty times the attraction of gravity.

For a complete account of the theory of Arrhenius, the reader is referred to his own excellent book *Worlds in the Making*, 1908. The radiation-pressure theory has been of the very greatest assistance in dealing with the corona, for the reason that it provides us with a knowledge of an additional force acting in a direction in opposition to gravitation. Miller has published a series of excellent papers[2] enquiring into the question whether the coronal streamers exist in accordance with a modified Schaeberle mechanical theory, that their motions are produced by ejection, by the rotation of the sun, by the attraction of the sun and by the radiant pressure of the sun. For the purpose of the investigation, Miller examined the excellent series of photographs of the corona obtained by the Lick Observatory expeditions from 1893 to 1918, inclusive, also plates secured by himself in 1905 and 1918, and Lowell photographs taken in 1918. The conclusions drawn are that the force of repulsion is surprisingly large, being almost equal to the attraction of gravitation, and as a result, it is unnecessary to assume the very large velocities of Schaeberle's original theory. The facts accumulated seem to be in fairly satisfactory accord with the theory of Arrhenius expressed as follows:[3] "It is very probable that those drops, for which gravitation is just compensated by the pressure of radiation, will be the chief material of the inner corona. For drops of other sizes are selected out, the heavier ones by falling back to the sun, the lighter ones by being drawn away by the pressure or radiation, so that just those drops which, so to say, swim under the equal influence of gravitation and pressure of radiation will accumulate in the corona."

[1] *Sitzungsberichte der math.-phys. Classe der k. b. Akademie der Wissenschaften zu München, 31*, 293, 1901.
[2] *Astrophysical Journal, 27*, 286, 1908; and *33*, 303, 1911; and also *Publ. A. S. P., 32*, 207, 1920.
[3] *Lick Observatory Bulletin, 1*, 152, 1902.

While the mechanical theory supplemented by that of radiation pressure seems to have solved many of the perplexing questions regarding the corona, there are still many difficulties to be surmounted before we can feel ourselves on thoroughly sure ground. It is hard to believe, for instance, that the polar rays have no objective existence, as demanded by the mechanical theory and exist only by a perspective projection of the equatorial streamers. It is unquestionably necessary to take into consideration magnetic and electric forces. Like radiation pressure and gravitation, these forces modify the other effects in a quantitative manner.[1]

That matter can exist in the finely divided state required by the theory of Arrhenius was shown[2] by "the eruption of Krakatoa, which drove the fine ashes up to an elevation of 30 km (18 miles). The finest particles of these ashes were slowly carried by the winds to all parts of the earth, where they caused, during the following two years, the magnificent sunrises and sunsets which were spoken of as 'the red glows.' This glow was also observed in Europe after the eruption of Mont Pelée. The dust of Krakatoa further supplied the material for the so-called 'luminous clouds of the night,' which were seen in the years 1883 to 1892 floating at an elevation of 80 km (50 miles), and hence illuminated by the light of the sun long after sunset."

If the temperature of the inner corona is approximately 5000° C (see p. 299), it is difficult to see, as was pointed out by Abbot,[3] how matter can exist in the solid or liquid state or how the dust-particles of the inner corona can be "drops of liquid metal."[4] Another criticism of almost insurmountable character is that voiced by Eddington.[5] Owing to the fact that conditions in close proximity of the sun cannot be duplicated in the laboratory, we are ignorant of the true laws of radiation-pressure, which may have "encouraged quite exaggerated ideas of the possible effects of radiation-

[1] See Pringsheim, *Physik der Sonne*, 330, 1910.
[2] *Worlds in the Making*, 7.
[3] *Lick Observatory Bulletin*, 5, 20, 1908.
[4] *Lick Observatory Bulletin*, 2, 188, 1904.
[5] *Monthly Notices, R. A. S.*, 80, 723, 1920.

pressure." The "upper limit" to its power of supporting or driving out matter has been calculated by Eddington, and has been found to be equivalent to a pressure of 2 dynes per sq. cm. This can be likened to a wind of this strength, and the exact effect of any material will depend on its power of absorption, — of stopping the wind instead of letting it blow through. Allowing an ample margin for uncertainties of observation, Eddington calculates that the "pressures of radiation cannot carry a total weight of more than a milligram per sq. cm." Applied to the chromosphere, the density is found to be of the approximate size of 10^{-12}, a quantity which indeed appears so absurdly small that it seems to contradict all our ideas concerning prominences. The density of the corona and in comets' tails on the same hypothesis is a thousand times smaller, or 10^{-15}.

Apparently therefore, the radiation-pressure theory is not entirely free from perplexities, but these difficulties may not be entirely insurmountable. Before further progress is made we must ascertain, by observational means, the size and the number of particles per unit volume forming the corona at different distances from the sun, and also the temperatures according to the Stefan and Wien-Planck formulas. The luminosity of the corona apparently is caused by particles which are heated to incandescence by solar radiation and which scatter sunlight, the particles being subject to gravitation, to radiation pressure and to electromagnetic forces largely unknown. Owing to their proximity to the sun, these particles cannot be in the solid or liquid condition and must therefore exist in the gaseous state. The molecules of the coronal gases strongly illuminated by sunlight probably act like the fine particles of a fog in scattering light. According to Fabry,[1] the part of the luminosity of the corona which gives the continuous spectrum may be due to this diffusion and not to reflection by small particles. As the result of some experiments on the diffusion of light by air, Fabry estimated that a truly gaseous corona having a density only one-thousandth-millionth that of air at atmospheric pressure would scatter sufficient sunlight to ac-

[1] *Observatory*, 41, 211, 1918.

count for the luminosity of the corona, and the polarization effects which have been observed. The explanation by Fabry has very much to commend it, but it is very much to be doubted whether it is based on sufficient experimental evidence. Moreover, it is difficult to see why the light of the corona, if caused by molecular scattering, is white in color and not blue like the sky.

The theory of ionization which has already been so successful in furnishing an explanation for many of the difficulties connected with the flash spectrum, the chromosphere and sun-spots is but a branch of a larger theory of photo-electricity dealing with the production of light by the passage of electricity through gases. The very excellent *Report on Photo-Electricity* by Hughes, published by the National Research Council, 1921, has been freely drawn upon for the information given below.

Photo-electric action involves ionization and radiation. When an electron strikes an atom and a transfer of energy takes place, there may be complete ionization, as shown by the production of positive and negative ions, or there may be partial ionization, i.e., a disturbance of the atom which is not detectable as ionization but is shown by the production of radiation. Both radiation and ionization are caused by the action of electrons in their bombardment of atoms. The ionizing potential has been defined as the least potential through which an electron, starting from rest, must fall to acquire sufficient kinetic energy to enable it to ionize a normal atom on impact. Spectroscopically, this means that the atom is now in a position, after capturing an electron, to emit the whole arc spectrum. The radiating potential, on the other hand, has been defined as the least energy necessary to remove an electron from an orbit normally occupied, to an orbit farther from the nucleus and normally unoccupied. In practice, this is almost invariably the orbit from which the electron, dropping to its innermost orbit, gives out the first line of the principal series (or combination series). Hence radiating potentials are usually associated with single line spectra.

Ionization and radiation potentials can be calculated from the corresponding spectral lines by the simple relation

$$Ve = \frac{hc}{10^8\lambda}$$

where e is the charge carried by the electron, h is Planck's constant, c the velocity of light, λ the wave-length measured in angstroms and V the voltage. Putting in the known values of the constants, the above equation reduces to

$$V \text{ (volts)} = \frac{12331}{\lambda \text{ (angstroms)}}$$

As has been shown in the case of hydrogen (see Chapter XVI) radiation takes place and light is emitted when the electron returns to an orbit nearer to the nucleus than the one to which it had been displaced. Ionization takes place when the electron returns from an infinite distance.

Perrin[1] has suggested that photo-electric action is probably one of the most fundamental and important occurrences in nature since radiation plays a very decisive factor in determining chemical reactions, fluorescence and phosphorence, radioactivity, cosmical evolution and changes of state. According to Millikan,[2] an atom which has lost an electron photo-electrically may sometimes later regain an electron. This electron will pass from one Bohr orbit to another on its way to the orbit it will finally occupy in the normal orbit. Apparently therefore, it will need but little additional energy on the part of the impinging electron to ionize an atom, or drive the electron to infinity, when the electron happens to be in one of the outer orbits on its way inwards to the orbit normally occupied.

Since the heavenly bodies, the sun, the stars, nebulae, etc., are radiating bodies, a knowledge of the laws underlying photo-electric action is of vital importance to the solution of astronomical problems. Unfortunately until recently, little was known of these laws, but with the advent

1 *Annales de Phys.*, *11*, 5, 1919.
2 *Physical Review*, *9*, 378, 1917.

of the electron theory, the Bohr theory of atomic structure and more recently Saha's theory of ionization, a great interest has been stimulated in this field of activity. Unquestionably we are on the eve of many important spectroscopic discoveries, so that many of the facts which have been regarded as simply empirical will receive an adequate explanation. It is of the utmost importance therefore that a thorough study be made of ionization and radiation potentials, for it is by this means that the advances in theory are to be secured.

Saha's theory of ionization (see Chapter XVII) has already been very successful in interpreting the importance of enhanced lines in the flash spectrum and in furnishing an adequate explanation of the differences between the Fraunhofer spectrum, the sun-spot spectrum and the chromospheric spectrum. The fundamental basis of this theory is that the electrons obey the same laws as gases, or, in other words, that they will have the same energies as any of the atoms. Hence from a knowledge of the temperature and pressure, it is possible to calculate the degree of ionization reached, if the ionization potential of the element is known.

Cannot this same theory, so successful in the case of the chromosphere, be expanded so as to furnish an adequate explanation of the cause of radiation in the corona? If successful with the corona, perhaps some of the problems connected with the emission of light in nebulae will find a similar elucidation.

It has been very difficult to understand the process whereby the coronal particles are enabled to emit light at the very great distances of ten million miles from the surface of the sun, under conditions of very low pressure and very long mean free path. But the corona is an appendage of the sun, and somehow or other (we have never realized just how) it may be possible for the corona to borrow some of its radiation from the sun. But how about a body like the Orion nebula? It gives a bright-line spectrum. Are astronomers to keep on saying, as they have for a number of years, that the Orion nebula emits light because the kinetic energy causes the particles to be heated and that the luminosity is wholly the

result of heat? Is heat also the cause of the emission of light by such a far-flung nebula as the one in Cygnus (*N. G. C.* 6960, 6992)? It is excessively difficult to imagine a body of such vast dimensions heated to luminosity but yet surrounded by the intense cold of inter-stellar space. Apparently some cause other than that of temperature must be sought.

In the *Contributions from the Mt. Wilson Observatory*, No. 241, Hubble gives a "General Study of Diffuse Galactic Nebulae." He finds these nebulae concentrated along two belts in the heavens, one the Milky Way and the other the belt of bright helium stars which define the local cluster, very few nebulae being found in the vast regions between these two belts. The spectral characteristics of the galactic nebulae and the stars with which the nebulae are associated are of the greatest interest. Sixty-two nebulae, lying outside the Magellanic clouds, investigated by slitless spectroscopes of various dispersions, fall into two groups: Group 1, containing thirty-three nebulae giving predominantly continuous or absorption spectra, and Group 2, of twenty-nine giving predominantly emission spectra. The members of the first group with continuous spectra have generally a smooth, cloudy structure, and most of them are found in our local cluster. The stars associated with the nebulae in these two groups differ radically in their spectral types: stars involved in nebulae with continuous spectra are nearly all of type B1 or later, while those involved in nebulosity with emission spectra have spectra of Bo or earlier and rarely show bright lines. The stars associated with planetary nebulae show a similar relation, in fact, there is a steady progression as shown by the following table:

Nebulae	*Spectra of Associated Stars*
Small planetaries	Wolf-Rayet
Large planetaries	Intermediate between Wolf-Rayet and Oe5
Extended emission	Oe5 and Bo
Extended "continuous"	B1 and later.

"This intimate relation between the spectral type of nebulae and of involved stars raises a presumption that

one is a consequence of the other. It seems more reasonable to place the active agency in the relatively dense and exceedingly hot stars than in the nebulosity, and this leads to the suggestion that the nebulosity is made luminous by radiation of some sort from stars in certain physical states. The necessary conditions are confined to certain ranges in stellar spectral type, and hence are possibly phenomena of effective temperature. The nebulous material itself must be in a physical state sensitive to stellar radiation, and close enough for the density of radiation to be effective. The abrupt transition from emission to 'continuous' nebulosity between spectral types B0 and B1 suggests a critical point in the spectral sequence, or possibly effective temperature, below which stellar radiation is incapable of exciting nebulous material to emission luminosity. From thence down the spectral sequence, the luminosity gives a continuous spectrum and probably partakes more and more of the nature of reflected light."

The theory of Hubble finds two obstacles: first, it is necessary to locate the stars associated with the galactic nebulae and have the stars always of the proper spectral type to harmonize with the theory; and second, it is necessary to assume that the luminosity from the star can be active at very great distances. Stars were found by Hubble in nearly every case to satisfy the first point. Regarding the distances raised by the second obstacle above, it was necessary to assume that in the nebulosity surrounding Rigel, the light from the star is capable of producing luminosity in the surrounding nebula at the enormous distance of twenty light-years, or twelve million times the distance of the earth from the sun.

Already as early as 1913, Hertsprung[1] showed that the Merope nebula involved in the Pleiades shines with a total luminosity that can be readily explained as being due to reflected starlight.

The conclusion of Hubble is that the luminosity of galactic nebulae is derived from stellar radiation. If this were a simple case of reflected starlight, the spectra of the nebula

[1] *Astronomische Nachrichten*, 195, 449, 1913.

would agree exactly with the spectra of the associated stars; but such is found not to be always the case. Hubble remarks, "It is doubtful whether or not a mass of diffuse nebulosity isolated in space and with no stars involved could hold together and at the same time shine by light generated by collisions of molecules. At temperatures corresponding to intensity-distribution or width of lines in nebular spectra, the average speeds of the molecules would be so high compared with the velocities of escape that the nebulosities would probably dissipate rapidly. On the other hand, if molecular speeds were sufficiently small to admit of cohesion in the mass, the nebulosity would probably be too cold to radiate light. This argument suggests that diffuse nebulosity is not intrinsically luminous, but is rendered so by external causes."

If it is possible to discover the mechanism whereby the nebulae are rendered luminous, the same mechanism will probably explain the cause of the coronal radiation. Although the emission spectrum of the corona differs radically from that of nebulae, the former showing the "coronium" lines and the latter those of "nebulium," yet in a sense the corona is a nebular appendage, very feeble in luminosity compared with the sun, and moreover it immediately surrounds the sun and is not at great distances as in the case of the nebulae. It is entirely likely that each and every star has a corona surrounding it, but these coronas can never be rendered visible to astronomers since the total light of each corona must be comparatively feeble compared with the luminosity of the sun which it surrounds. Milne[1] has shown that the light of the corona can have no sensible effect in modifying the spectrum of the sun.

The mechanism for explaining the radiation of corona and nebulae unquestionably is found in the electron. The sun and the stars are vast radiating spheres at very high temperatures, and from each of these suns, billions of electrons are shot off every second of time. The number of the electrons emitted depends on the intensity of the radiation while the energy of the electron depends primarily on

[1] *Phil. Trans. Roy. Soc'y, A* 223, 201, 1922.

the temperature. The energy of the electrons will carry them to the greatest distances from the radiating body in the case of the very hottest stars.

The *predominating* spectrum of the corona is a continuous one. The emission spectrum of coronium does also appear superposed on that of the continuous spectrum, but its total radiation is comparatively feeble compared with the continuous spectrum. Since the sun is a star of G type, its nebular appendage, the corona, exhibits a spectrum quite in conformity with Hubble's observations of nebulae. Schuster[1] has shown that bright spectral lines can only be produced on a continuous background when there is a sufficient scattering to dim the background. For this same reason, there are no stars showing bright lines in their spectra associated with nebulae giving emission lines. The only possible exception, so far noted, is in the star γ Cassiopeiae. It was shown by Milne (*loc. cit.*) that this star undoubtedly possesses an extensive hydrogen atmosphere in which the general absorption is small compared with the scattering and selective emission. This star, however, is one of "peculiar" Bo type, and its peculiarities are further shown by measures of its temperature by Wilsing and H. H. Plaskett who independently find the value 6800°, while the mean temperature of the average Bo star is 10,700°.

In spite of the pitifully small amount of positive knowledge regarding the laws underlying photo-electricity, the following electron theory of the corona is proposed, namely, that the corona is a manifestation of photo-electric effects. As already stated, the sun is the source of enormous radiation (compared with terrestrial standards). The high temperature of 6000° C, with moderate pressures at the photosphere amounting to a small fraction of a terrestrial atmosphere, permits a ready discharge of electrons. The general magnetic field of the sun aids in this discharge. The high temperature radiation is no doubt of very short wave-length akin to X-rays. It is probable that most of the photo-electric effects produced are due to these short wave frequencies. On account of the intense radiation, the electrons leave the

[1] *Astrophysical Journal, 21,* 1, 1905.

sun in vast numbers and with energies that carry them to great distances from the sun. The electrons quickly reach the corona, a region of very minute densities. When the electrons in their flight outwards from the sun impinge on atoms, their energy is transformed by displacing the outer electrons of these atoms from their positions normally occupied. These external atoms thus become centers of disturbances from which are radiated various forms of energy which may be manifested as light, electromagnetic and photo-electric effects, phosphorescence, fluorescence, etc.

According to the researches of Hale and his co-workers at Mount Wilson, sun-spots are the centers of very powerful electromagnetic disturbances, and from them are shot out very intense electronic discharges that reach the earth and display themselves in the aurora borealis. The energy of the electrons is greatest near the sun-spots on account of the greater intensity there of the magnetic field. At the times of sun-spot minimum, the spots draw in towards the solar equator. Hence when the sun is quiescent, as it is at minimum of sun-spots, the effect will be that of very long streamers going out in straight lines near the sun's equator and very short and curved rays near the poles. Since the general magnetic field of the sun is very weak compared with the strength of the fields found in spots, the polar rays will be short and curved while the equatorial streamers will be long and straight. Since the sun-spots are confined to a zone near the equator we have the typical corona of sun-spot minimum. After passing the epoch of minimum of spots on the sun, the discharge of electrons is not limited to regions near the equator but is displayed in heliographic latitudes farther north and south. Consequently, the corona takes on first a rectangular shape, and then a contour more and more circular as the time of sun-spot maximum is approached, the weak polar brushes characteristic of sun-spot minimum being meantime covered up by more intense radiations.

Owing to the greater average vigor of electronic discharge at sun-spot maximum, there should be a greater intensity of the emission lines of the spectrum of the corona at maxi-

mum than at minimum of spots; and this is found actually to be the case.

Although the corona may have some radiation which is inherent in itself as a separate self-contained entity, it is probable that by far the greatest part of the coronal radiation is borrowed from the sun in the following manner:

A. By the scattering of light from the sun itself by the coronal atoms.

B. By radiation from the sun passing through the atoms of the corona and,

(*a*) ionizing them, i.e., putting them in a state in which they can radiate,

(*b*) partially ionizing them.

This second effect can be manifested in two different methods: (1) by the electron returning to its normal position so that radiation is given out, or (2) it is easier for the electrons freed in Process *a* to ionize these partially ionized atoms and so cause them to give out more electrons.

The photo-electric theory of the corona herein suggested differs from other theories previously advanced by recognizing the recent important discoveries of modern physics that the electron is the carrier of electricity.

The photo-electric theory, when extended to the nebulae, is equally effective in explaining their peculiar characteristics. In obedience to this theory, the prediction is made that "coronium" which causes the emission spectrum in the corona, and likewise "nebulium," the cause of the bright line spectrum of nebulae, will be found to take their origins from atoms doubly, triply or more times ionized and which belong to some of the lighter gases in the early part of the periodic table. In view of the great differences between the corona and nebulae it is altogether likely that nebulium and coronium do not spring from the same chemical element.

It is now more than forty years since the first attempt was made by Huggins to photograph the corona in full sunshine. The authority of his name, great in the annals of spectroscopy, gave a degree of plausibility to the problem. After attacking the question from all sides by a great variety of different methods, many of the ablest astronomers engaging in the quest, the goal seems as far distant as ever. The task to be overcome is to separate the light of the corona from the strong illumination of the sky. The chief names connected with this work are those of Hale, Riccò, Deslandres, Wood and Hansky. It was natural that the methods so successful in photographing the prominences should be first tried, and in order that the atmospheric glare might be reduced as much as possible, the observations were made from mountain tops, Pike's Peak and Mt. Etna being occupied for this purpose. No success being secured, a series of attempts were made by heat-measuring instruments like bolometers or thermopiles. Photographic methods, of using color filters and plates sensitive to different parts of the spectrum have been thoroughly tested. Since the Great War when such noted success was attained in airplane photography by using plates sensitive to the deep red, attempts were revived on the corona. Lindemann had found it possible to photograph stars of the first magnitude near the sun. Each and every one of the plans, however, at times carried out with great skill and ingenuity, have always ended in the same manner, — failure to photograph the corona in full daylight.

The observations by Abbot in 1908 and those by Kunz and Stebbins in 1918 have shown the cause of the failures, namely, the intrinsic feebleness of the corona. Even in the brightest parts, the inner corona is no brighter than the surface of the full moon which has a brilliancy six-hundred-thousand times less than the sun. The corona is about equal to the intensity of the illuminated sky at eight or ten degrees distant from the sun, but close to the sun's edge the light of our central luminary is so overpowering that it appears indeed well-nigh impossible to photograph the corona in full daylight. As a consequence, knowledge of the corona will advance very slowly, since the opportunities afforded for investigating it will come only at the very rare intervals of total eclipses of the sun.

CHAPTER XX

THE EINSTEIN THEORY OF RELATIVITY

EINSTEIN'S theory of gravitation has been justly regarded as the greatest triumph of mathematical reasoning that has taken place since the time of Newton. It is safe to say that no scientific achievement of recent years has aroused so much popular interest and enthusiasm as that evoked by the verification of the Einstein prediction from observations made at the total eclipse of May 29, 1919.

The first step in any scientific investigation is to get at the facts, derived from observation usually by a series of measurements. Great precision, patience and care are necessary to enable the observer to record the true facts devoid of any inferences or illusions of the mind. Lord Kelvin has said that, " Nearly all of the greatest discoveries of science have been but the rewards of accurate measurement and patient, long-continued labor in the minute sifting of numerical results." After the observations have been secured, they are classified and analyzed and tested to see whether they will conform to some known law. The laws of nature differ greatly from human or civil laws since the former must be universally true and must apply under all conditions. If a law of nature is found to be deficient, even in some minor detail, it must be revised to satisfy the conditions, or, if this is impossible, then the law must be discarded.

The grandest and best known natural law is that of gravitation discovered by the great Newton. Its importance lies primarily in the fact that it applies to all bodies, it is universal. In the two and a half centuries that have elapsed since the falling of the apple, the law of gravitation has experienced one grand triumph after another, with the in-

evitable result that we have come to look upon this law as practically infallible. Other laws may come and go and be revised into changed form, and go on again to be again and again revised, but the law of gravitation has stood firm without change, with the enunciation of its principle in the same form as when handed to us by Newton. Every body in the universe attracts every other body in the universe with a force that is proportional to the product of the masses and inversely to the square of the distances apart.

And now we are told that the law of gravitation must be discarded, that space is curved and that we live in a world of four dimensions. The mind reels, and refuses to be convinced. Common sense tells us, we say, and the experience of the ages has proven, that space has but three dimensions, length, breadth and thickness, so why say such an apparently foolish thing that time, which we *know* has nothing to do with space, must be considered as a fourth dimension? The average man of intelligence immediately calls to mind some of the properties of the mathematician's space of four dimensions, — a man enclosed in a steel-proof vault, if living in a four-dimentional space, could get outside of the vault without passing through any of the walls. One smiles incredulously, and thinks of a remark by Bertrand Russell that " mathematics may be defined as the subject in which we never know what we are talking about, nor whether what we are saying is true."

Is the theory of relativity of Einstein an unreality in the brain of the mathematician, or must we accept it as true and believe in a four-dimensional space? If the Einstein theory is accepted, then as an important consequence the law of gravitation *must* be revised, there is no middle course. The new theory states that there is no " force " of gravitation, for this " force " is but one of the inherent properties of four-dimensional space. To decide which of the two conflicting hypotheses best represents the law of gravitation, Newton's or Einstein's, we shall have to pass in review the salient facts. Science desires the simplest explanation. Einstein's own conception of the law of gravitation, as expressed in the New York *Times* is, " Please imagine the

earth removed, and in its place suspended a box as big as a room or a whole house, and inside a man naturally floating in the center, there being no force whatever pulling him. Imagine further, the box being, by a rope or other contrivance, suddenly jerked to one side, which is scientifically termed '*difform motion*,' as opposed to '*uniform motion*.' The person would then naturally reach the bottom on the opposite side. The result would consequently be the same as if he obeyed Newton's law of gravitation, while, in fact, there is no gravitation exerted whatever, which proves that difform motion will in every case produce the same effects as gravitation.

"I have applied this new idea to every kind of difform motion and have thus developed mathematical formulas which I am convinced give more precise results than those based on Newton's theory. Newton's formulas, however, are such close approximations that it was difficult to find by observation any obvious disagreement with experience." Does this theory of Einstein concerning a man falling from the top of a step-ladder to the floor of a room really furnish a *simpler* explanation than the classical law of falling bodies of Newton? If it does, then a very radical change in our modes of thought must take place.

History shows that the present is not the first time that the perfect science of astronomy has been forced to change its point of view. In the early days of civilization it was believed that the earth was flat, — and this notion is still not quite eradicated from human thought. Later was evolved the theory that the earth was the center of the universe and about it revolved the sun, moon, planets and stars. The mechanism required by the Ptolemaic system to explain the motions of the heavenly bodies by cycles and epicycles was such a cumbrous one, that it led to a remark by a former king of Spain that if he had been present at Creation he could have furnished the Creator with some very valuable suggestions. The work of Copernicus, Tycho, Kepler, Galileo and Newton revolutionized scientific thought, and as a result the earth was displaced from her important position as the center of the universe. Although the geocentric point of view is still retained in some of our scientific explanations, we realize that the sun is the center of our system, with the earth occupying no more exalted a position than that of being but one of the planets. The Newtonian mechanism reduced celestial motions to the greatest simplicity. In obedience to the law of gravitation, every planet describes a perfect ellipse about the sun as focus, and these elliptical orbits would repeat themselves indefinitely were it not for the gravitational forces arising from the other planets. After allowing for all of the planetary disturbances, or "perturbations," Newcomb found that the orbit of the innermost planet Mercury was rotating in its own plane at the rate of 42 seconds of arc per century in excess of that required by the traditional theory. Various attempts were made to explain away this discrepancy in the motion of Mercury — by assuming a planet or planets inside the orbit of Mercury, or outside of its orbit, by postulating a belt of matter in a flattened disk or series of ellipses surrounding the sun, or by presupposing that the sun has an oblateness of shape and distribution of mass different from that usually taken for granted — but all to no avail. In every case, the assumption of mass required to produce the observed effect on Mercury would have caused disturbances not observed in the other planets. The solution of the problem came only with the theory of relativity which furnished a motion of the perihelion of Mercury of 43″ per century, in almost exact agreement with the observed discrepancy. And so, when in addition, the observations of the 1919 total eclipse gave deflections in accordance with the Einstein prediction, the confirmation of the theory of relativity seemed almost complete.

Newton's law, however, is not invalidated by the latest discoveries but rather is supplemented by them. It is possible in very few instances, and as the result only of the most refined measurements, to be able to detect the difference in observed effect between the Einstein and the Newtonian laws. In addition to his great work on gravitation, Newton proposed an erroneous theory of light. According to this theory, light consists of minute corpuscles expelled

from a luminous source with high velocities. In the estimation of Kayser,[1] " Newton's errors impeded science even to the middle of the nineteenth century." It was not until the observations of Hooke, Huyghens, Young and Fresnel showed the corpuscular theory to be untenable that the wave theory was finally established. But how do the waves of light travel from the sun to the earth? It was necessary for the physicist to invent some material medium for their propagation, and hence the existence of an imponderable and universal " ether " was devised. With the discovery of the laws of electromagnetism, it was shown by Maxwell that electromagnetic disturbances also were propagated with the speed of light, and the conclusion was drawn that light itself must be electromagnetic in character. Additional functions were imposed by physicists upon the universal medium with the result that Maxwell and Kelvin were able to make estimates of the density and rigidity of the ether with almost as much assurance as if they had been dealing with perceptible matter. (More recent researches have shown that not only is light electrical in nature but so also is mass and energy.)

Light and all electromagnetic manifestation were believed to be actions taking place in the all-pervading ether. Light from the distant stars reaches us in the form of wave motions in the ether, and it has been necessary to assume that the sea of ether between us and the distant stars is unbroken. Moreover, in order to account for astronomical aberration and other phenomena, it was proven beyond doubt that the ether must necessarily be at rest, that it pervades everything but that it is not dragged about by ponderable material. Since motions of all kinds are relative in their nature, it was of the utmost importance to theories of physics that a state of absolute rest should exist in nature and this appeared to be found in the condition of the ether. Accordingly, attempts were made to detect the drift of the earth through the motionless ether. In 1887, the first experimental determination was carried out by Michelson. The same experiment was later repeated by Michelson and

[1] *Handbuch der Spectroscopie, 1, 5.*

Morley, by Morley and Miller, and quite recently by Miller alone. This experiment has been described so frequently that it will be unnecessary here to go into details. The velocity of light was known to be, in round numbers, 186,000 miles per second, and this was supposed to represent the velocity of the wave motion through the ether. The velocity of the earth in its orbit is 18 miles per second, and hence if the ether is stationary with respect to the sun, the drift of the earth through the ether should be at this speed. Accordingly, if a beam of light reaches the terrestrial observer in the direction of the earth's motion, it will be traveling with respect to and overtaking the earth at a speed of 185,982 miles per second, while if the beam of light comes in the opposite direction its velocity with respect to the observer will be 186,018 miles per second. Although it is impossible to measure the velocity of light along a single straight course with sufficient precision to compare the two velocities above, nevertheless these velocities can be compared by a differential method. This was accomplished by the Michelson-Morley experiment. This consisted in dividing a beam of light by means of an unsilvered mirror, allowing each half of the beam to travel the *same* distance in directions perpendicular to each other, and then reflecting the two beams back to the same point at which they were originally separated, and then recombining them. It is evident that on account of the motion of the earth, the path through the ether of the half beam which is traveling parallel to the direction of the earth's orbital motion must be slightly longer than the other half of the beam. Consequently, when the two halves of the beam are reunited, the waves of light should be a little out of phase. By turning the apparatus through a right angle, a check is obtained on the equality of the distances traversed by the two beams. The precision of the experiment was so great that it should have been possible to detect the drift of the earth through the ether equal to one-tenth of its orbital velocity about the sun. But no effect whatever was detected and there was no indication that the earth was moving at all through the ether.

To make the signification of the Michelson-Morley experiment plain, a similar trial can be readily performed by any swimmer in a river where there is a current. Will it take longer to swim 100 yards up-stream against the current and back to the starting point with the current, or 100 yards across the stream and back to the starting point?

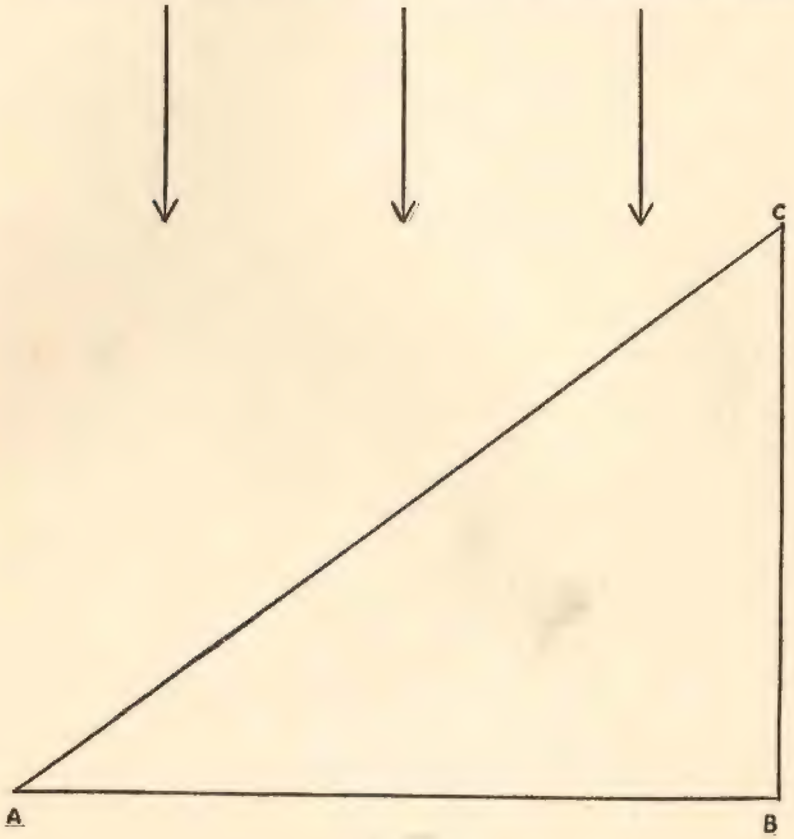


FIG. 5

Suppose the speed of the swimmer is 25 yards a minute in still water and the current flows at 15 yards a minute. The speed against the current is 10 yards per minute, and that with it 40 yards per minute. It will thus take ten minutes to go the hundred yards up-stream and only $2\frac{1}{2}$ minutes for

the swim back to the starting point, or $12\frac{1}{2}$ for the round trip, though in still water it would have taken only 4 minutes each direction, or 8 minutes for the complete trip. In going directly across the stream, part of the swimmer's strength is spent in combating the current. To reach a point, B, diametrically opposite the starting point A, it is necessary to start up-stream in the direction of C so that AC represents the distance traveled in still water and CB the amount he has drifted down. AC and CB are in the ratio of 25 to 15, and since ABC is a right-angled triangle the side AB must correspond to 20. Since the distance AB across the river is 100 yards, the length AC is 125 yards, and the time spent in swimming will be 5 minutes, with another 5 minutes for the return journey, making total of ten minutes to cross the stream and back, while twelve and a half minutes were spent going up-stream and back. The ratio $12\frac{1}{2}$:10 minutes may be written

$$\frac{1}{1-\left(\frac{15}{25}\right)^2}$$

To make this experiment quite general, suppose c is the velocity of the swimmer and v that of the current. Then the times spent for the round trips parallel to and at right angles to the current are in the ratio

$$\frac{1}{1-\frac{v^2}{c^2}}$$

The speed of the swimmer is analogous to the velocity of light in the Michelson-Morley experiment, while the current of the river corresponds to the drift of the ether or the velocity of the earth in its orbit. Since c, the velocity of light, is 186,000 miles per second, the denominator of the above ratio will become equal to $\frac{1}{2}$, if v is 161,000 miles per second. If $v = c$, the denominator becomes equal to $1 - 1$, or zero.

The most obvious explanation of the failure of the

Michelson-Morley experiment to detect the drift of the earth is that the ether is stationary with respect to the earth or is carried along by it. But if we admit this possibility, we are in a quandary to explain the aberration of light from the stars. Everyone is familiar with the fact that on a rainy day when there is no wind the rain falls vertically, and to keep dry, when standing still, an umbrella is held over one's head. If the holder of the umbrella starts to walk he tilts the umbrella forward in the direction of his motion, for experience has told him that only by so doing can he keep dry. The faster he walks the more the umbrella is tilted forward. This is a simple case of relative motion. So when a telescope is pointed in the direction of a star, the telescope tube must be tilted forward by an appreciable angle so that the rays from the star may pass down the tube to the eye of the observer. The angle through which the telescope has to be inclined is known as the angle of aberration. This angle was discovered by Bradley in 1728. Its value is 20″.47. On account of the great precision of modern astronomical measurements this angle is regarded as one quite large in size.

But how explain the Michelson-Morley paradox that the earth must be drifting through the ether while at the same time the effect of this drift has never been detected? Apparently there is no way out of the dilemma but that our ideas must in some manner be revised. In 1893, a satisfactory explanation was offered by Fitzgerald, and in 1895 independently by Lorentz, that the negative result of this experiment becomes quite intelligible if it is assumed that when a body is in motion through the ether its dimensions in the direction of motion become slightly shorter than when it is at rest. This would indeed seem to be a strange and a highly arbitrary hypothesis if unsupported by other scientific evidence. The work of Lorentz and Larmor on the electromagnetic theory showed that it was necessary to assume that a body when in motion does actually contract by just the amount demanded by Fitzgerald's explanation. If this hypothesis is true, then as a result we are inevitably forced to the conclusion that time also must be measured in a different manner for an observer at rest and for one in motion. The Fitzgerald contraction is not merely an idle arbitrary speculation, but after repeated experiments it has been shown to be true and mathematically exact in the well-known laws of electromagnetic forces.

The amount of contraction depends on the velocities, and in the majority of the cases of our experience, or for average velocities, is excessively minute. In the case of the earth the contraction is only one part in 200,000,000, which corresponds to a contraction of $2\frac{1}{2}$ inches in the earth's diameter in the direction of its motion. The Michelson-Morley experiment therefore failed to detect the motion through the ether for the simple reason that the dimensions of the apparatus were actually automatically contracted by an amount just sufficient to compensate for the effect sought. Other ingenious experiments, electrical and optical, were tried for the purpose of detecting the drift through the ether, but always with the same result. There thus appears to be a "conspiracy" among the various agencies at work to prevent man from measuring his motion through space.

In 1905, Einstein published his restricted Principle of Relativity that "it is of necessity impossible to determine absolute motion by any experiment whatever." According to Einstein, all motion is relative, and no experiment can be possibly devised so as to decide which of two systems is at rest and which in motion. It is therefore impossible by any experiment to detect uniform motion with respect to the ether. Hence the assumption of the ether, brought into physical science for no other purpose than to explain the propagation of light, becomes entirely unnecessary. If the ether has no position whatever in space, the statement that it exists has no meaning. Hence the first consequence of the theory of relativity was to discard the ether as superfluous. A second consequence is that the velocity of light with respect to two observers moving relatively to each other must always be the same, no matter in what direction the light is traveling, as the velocity must be equivalent to that when determined by an observer at rest, of 186,000

miles per second. These radical changes can exist only under the condition that certain relations, known as relativity transformations, exist between the space and time measurements made by the two observers.

The principle of relativity thus entails changes in our mode of thought of the most revolutionary kind, and our preconceived notions in consequence are turned topsy-turvy. Let us see a few examples. If an observer is traveling at the rate of 161,000 miles a second in a vertical direction his arm, 30 inches long, is of its natural length when extended horizontally, but is contracted to 15 inches when hanging by his side or raised vertically above his head. This you say is foolishness. Well, take a yardstick and measure the length of the arm. Horizontally the arm measures 30 inches on the scale, and vertically exactly the same 30 inches by the scale. Yes, but when you hold the scale vertically it too has been contracted and each inch on the scale is in reality only half an inch, so that the arm measures 30 *half-inches* or 15 inches. "Yes," you will say, "but whoever heard of anyone moving with such a colossal speed as 161,000 miles per second?" Why not? It is impossible to measure absolute velocities in space, and for all we know to the contrary we may be speeding along at this terrific rate. The β particles, referred to in Chapter XVI, move with velocities of 100,000 miles per second.

A conclusion perhaps even stranger than the foregoing must be drawn from the principle of relativity. Suppose observer A is moving through space at a speed of 161,000 miles per second relative to B, and allow each observer to hold an identical yardstick. On account of his fast flight, A's stick is contracted to half of the length it has when at rest, and hence B's stick appears to be twice the length of his own. But since motion is purely relative in character, B must be moving with respect to A with the speed of 161,000 miles per second, and hence B's yardstick is contracted; and it appears to be twice as long, half as long, or equal to the length of an identical stick, depending on which stick is the moving one or whether they both are at rest.

If the speed of the observer is increased beyond 161,000

miles per second, the contraction becomes greater and still greater; and at the velocity of light all lengths dwindle to zero and vanish. The observer changes to an object of two dimensions, length and breadth, but without thickness, but he himself is blissfully unconscious of his sorry plight. Distance is annihilated and so also is time. If traveling at the velocity of light, the observer could go to the most distant star without becoming a day or even a second older, for the reason that no time had elapsed. These paradoxes make the theory of relativity very difficult of comprehension to anyone who is not a mathematician and they seem moreover to controvert our "common-sense" view of things.

Everyone will agree that if one measuring rod identical in length with another can be twice as long, half as long or equal in length to the other, there must be something wrong somewhere with the method of measurement. Einstein inquired into our methods of measuring length and time and pointed out the lack of definiteness in the concepts of space and time as ordinarily used. What do we do when we measure the length of an object like a book? We take a foot-rule or meter stick and determine its "true" length. We measure the size of the book, however, only by comparing it with a scale whose length we suppose to be known. But what do we actually know of the length of the foot-rule? We take it for granted that it has been compared with some standard foot-rule or yardstick. We know the lengths of our measuring rods only by comparing their lengths with other rods, and so on and on through an almost endless series of comparisons, until we come to the Standard Yard preserved in London, or the Standard Meter kept in Paris. The latter is a rod of definite shape, of a certain particular metallic composition, and at a given temperature, the length between two specified lines is exactly a meter. The length of the meter is approximately one ten-millionth part of the earth's quadrant. What would happen if the earth and all it contains were suddenly contracted to half its present dimensions? All objects including ourselves and all measuring appliances would dwindle to half size. We would never have any idea that the earth had contracted if we kept our

attention on terrestrial objects. But lo, and behold, the sun has suddenly doubled its size! If the sun and the external universe could have contracted at the same time as the earth and the observer, we could never have become aware of the difference. The " true " length of a book or a rod thus depends on the definitions and postulates which we adopt. Manifestly there is no such thing as " absolute " space, everything is merely relative to the observer.

You will insist, however, that if there is no " absolute " space, there must certainly be " absolute " time, for time seems to go on quite independently of any observer. Each of us unconsciously feels that when we die, the world will carry on just about as before. Time and space thus seem on a very different basis. But how do we measure time? Ordinarily by a clock. We assume that the pendulum swings in a perfectly uniform manner and that the clock hands move equal distances in equal intervals of time. But how *prove* our assumption? We are forced for our definitions of time intervals to go back to the earth, and to assume that the earth is a colossal top set spinning on its axis, and its mass is so great that like a gigantic fly-wheel its motion *must* certainly be uniform. The assumption seems sound and all of the accurate measurements of astronomy are based on it. What would happen to the vaunted predictions of astronomy if the earth changed its speed of rotation? In fact, it was shown in Chapter IV that some suspicion has lately been cast on the uniformity of rotation of the earth, — and our time-keeper may after all be a faulty one. Apparently therefore, we seem forced to the conclusion, since time-measurements depend on measures of distances, that there is no absolute time any more than there is absolute space. The determination of both space and time consist essentially in the measurement of certain lengths, and such measures have no meaning except in relation to ourselves and our every-day experiences.

Let us return again to the measurements of the book. We recognize the object because we have seen other books. We glance inside the pages, and find a treatise on higher mathematics or some ebullition of modern fiction, both unreal and

devoid of meaning to our feeble intellect. We likewise recognize the foot-rule and we accept some one's word for it that this rule has been compared with other rods, etc., etc., and that we know its length. Applying the measuring rule to the book, and spending a few seconds of time in the operation, we find a length of eight inches. A Martian dropped to the earth would not recognize a book, for in the advanced civilization that is supposed to exist on the ruddy planet, books do not exist. Neither would he recognize the foot-rule, and certainly the marks that designate the inches would be utterly unintelligible. The simple process of measuring the length of a book would be completely impossible to the gigantic brain of the Martian. He has not been taught from his childhood up to measure with our particular rods.

The measurement of a length, simple though it seems, is after all a very complicated process. We see the book, and note that it occupies a definite position on a table in a room furnished as a library. Having two eyes, we have learned unconsciously to estimate the distance to the book, and so we telegraph the thought to our brain that we must reach forth the hand and pick up the book. (It is not necessary to trace further the train of thought.) But it is easy to see that in measuring the length of the book we are putting into practice the training of hundreds and even thousands of years, acquired at times with great difficulty by ourselves and our ancestors.

Knowledge thus comes to us only as a series of experiences or events. Each experience is perhaps an instantaneous photograph on the brain. But every photograph when taken requires a definite exposure-time, sometimes longer, sometimes shorter in length, depending on the intensity of the light and the speed of the photographic plate. And so there are brains which work slowly and those which grasp more quickly. We see therefore that throughout all of our existence we have tacitly assumed, without realizing it, that measures of space are not at all independent of time, and that durations of time are not devoid of their inherent reference to space. There are no durationless events, and each and every one of our experiences involves a consciousness

of both space and time. Thus neither space nor time is absolute, and every observation is relative to the individual observer. But each observer being confined to the earth, by common consent we have come to the conclusion that Truth is attained only when our observations agree with that of the average individual and that we are in error when we differ from the general average.

Throughout the whole of our scientific consciousness we have assumed that in agreeing with the average observer we have thereby derived the " true " length or have determined the " true " duration of time. The great triumph of Einstein consisted in making clear that the " true " measures of each observer, and hence of the average observer, are only relative in their nature and not absolute in value. Consequently, all of the observations with which we are familiar are relative and depend only on the individual as represented by the average observer. The method of advance was manifestly to divorce the series of events from the observer, and look upon them from the point of view of the objects themselves. This was Einstein's method. He assigned space and time solely to the observer, but gave to nature an unfamiliar combination of space and time of four dimensions. However, this is not the same four-dimensional space that has lately been much discussed by the mathematician, a space of length, breadth and thickness and a fourth dimension at right angles to the other three. The relativity world of four dimensions we have in reality been quite familiar with throughout our whole lives, as is signified by the words right-and-left, forward-and-backward, up-and-down, and sooner-and-later. The first three dimensions give the familiar world of *objects*, the four dimensions taken together furnish the world of *events*. In this four-dimensional world a particle occupies not one point, as we are accustomed to think of in space of three-dimensions, but a series of points representing its positions at successive instants of time. Its history then is represented by a line, called its " world-line." If an observer is admitted, he has his own world-line and immediately he imagines that his world-line, of all lines, is the most important in the universe.

He immediately proceeds to divide up the four-dimensional entity into a space of three dimensions with time as the fourth, and we have the world familiar to us all. But the theory of relativity rules out the observer from any consideration whatever, and there now results a space-time nature in which is scarcely recognized space and time. There is thus no " shape " to anything, no difference between straight and crooked, it is impossible to measure an angle, which is in fact the difference in direction between two straight lines. This four-dimensional world which was invented by Minkowski, naturally has no reality, it does not exist and its properties cannot be interpreted by our ordinary experiences. The fourth dimension at right angles to the other three is not even the time plotted as a quantity directly, but the product of time into the square root of minus one. This quantity, $\sqrt{-1}$, is known to every intelligent boy as the symbol of an imaginary quantity. Hence it is futile to attempt to assign to this unfamiliar and unreal world any of the attributes derived from the common experience of life. Many writers in their attempts to popularize have used such catch-phrases as " time is curved," " there is no *now*," " a phenomenon may be seen before it happens," and so forth and so on.

" Relegating space and time to their proper source — the observer — Einstein bids us contemplate the residuum of what we observe. This residuum is the true world. It is shapeless, because we have abstracted shape; yet it is metrical and has quantitative properties which can be expressed in mathematical terms. Clearly we cannot describe this true world in terms of familiar things, because the whole point of Einstein's theory is that we must subtract the ideas which we ourselves have added in order to form familiar things. Mathematics is the only language in which the inherent qualities of this unfamiliar world can be described. But though it seems unfamiliar, nature is left simpler by this purification. A closer unity is perceived in the bases of phenomena apparently diverse; and, for example, the effect of gravitation on light is clearly foreseen. Further, the laws of nature must relate to this four-dimensional residuum and

the space and time we ourselves introduce cannot be relevant. This led Einstein to the conclusion that Newton's law of gravitation, which refers to one particular separation of space and time, cannot be the exact law; and he proposed a new law applicable to the four-dimensional world."[1]

Although there is no distinction between straight and crooked in the four-dimensional entity, it is however possible to join two points or events by a certain unique track which plays a part corresponding to the straight line in our familiar life. This unique track is called a *geodesic,* and instead of being the shortest distance between two points — the important property of the straight line in ordinary space — the geodesic is of the maximum length. We see, therefore, what unfamiliar conceptions are involved in the theory of relativity, and how radically changed must be the point of view that makes the distance between two points a maximum and not a minimum!

Let us see some of the necessary consequences of the principle of relativity in its relation to the propagation of light. As already stated, this principle enunciates that the velocity of light is independent of the observer, or, stated in other words, that no matter what is the velocity of the observer the wave-front of an emitted beam of light is always a sphere with the observer as the center. According to the older views, a definite point of the ether, the source of light, was the center of the sphere, but according to the newer ideas it is the observer himself who is the center of the sphere. The observer is thus in a sense the center of the universe, he is at rest and the universe is carried by for his inspection. If an observer A is the center of a sphere, the wave-front will have advanced after time t so that the square of the radius of the sphere will be represented by

$$x^2 + y^2 + z^2 = c^2t^2$$

$$\text{or} \quad x^2 + y^2 + z^2 - c^2t^2 = 0$$

where the observer is the origin of coordinates and c is the velocity of light. For any other observer B, the wave-front

[1] Eddington, *Contemporary Review, 116,* 643, 1919.

will again be a sphere but with B as its center, and the mathematical equation will be

$$x'^2 + y'^2 + z'^2 - c^2t'^2 = 0$$

According to the relativity assumption, the sphere observed by A is identical with that observed by B. Hence a linear transformation between x, y, z, t and x', y', z', t' must transform either of the above equations into the other. If now we put $ict = w$ (where i is the imaginary quantity, $\sqrt{-1}$), then the equations reduce to $x^2 + y^2 + z^2 + w^2 = 0$ and $x'^2 + y'^2 + z'^2 + w'^2 = 0$, each of which represents a sphere in four-dimensional space. x, y, z, w form a set of orthogonal coordinates, and x', y', z', w' must represent a second set of orthogonal axes in this same space. In space of three dimensions we are familiar with such sets of axes. An observer at any one place chooses three axes, one north and south, the second east and west and the third vertically up and down. Another observer at a different place on the surface of the earth takes a similar set of axes with reference to his directions of north, east and vertical. But what are up and down, and north and south to one observer are not the same directions that appear to the other observer. A rotation of axes and a transfer of the origin will transform the set of axes of one observer into those of the other. Similarly in the four-dimensional space-time continuum the coordinates of A can be transformed into those of B by a rotation of axes. But the sphere observed by A being the same as that observed by B, or by any other observer, it therefore must appear as an objective reality. But A and B divide up the space-time continuum differently. Space and time depend only on the consciousness of the individual observer; hence the coordinates that A calls pure space and pure time will not be space and time to observer B but will be a mixture of the two. It is only the combination of space and time, not space and time separately, that represents reality independent of the peculiarities of the individual observer. The mathematical expressions by means of which x, y, z, w are rotated into x', y', z', w' are the

famous transformations of Lorentz which were derived a decade before Einstein's work was published.

Starting with these transformations and assuming that light follows a geodesic and not a straight line (which is now a meaningless term), Einstein developed his famous theory of gravitation. The only constant introduced into the discussion is *c* the velocity of light, the maximum velocity of which we have any observational experience. Virtually the only assumption made is the one of fundamental importance, that the velocity of light is identical to all observers. This is at best an assumption, and if it can be shown by any experiments that this premise is not true, then the whole Einstein structure will fall into ruins. By means of a little-used and very difficult branch of mathematics, a theory was developed which explains gravitation, the motion of Mercury and the gravitational attraction of the sun on light rays. As the author does not claim to be one of the original dozen who could understand Einstein's equations he will not introduce any further mathematical formulas. These newer conclusions will herald an advance over the old law of gravitation only on the condition that Einstein's theory represents the observed facts more closely than the theory of Newton.

We may perhaps obtain an inkling of the meaning of four-dimensional space by starting out with the properties of three-dimensional space, with which from childhood we have been familiar. In the world of *events* all four coordinates are necessary, for we never observe an event except at a certain time, and we are never cognizant of an instant of time without special reference to space. In discussing the laws of electromagnetic phenomena, it was shown by Minkowski that these laws could be represented by assuming a four-dimensional space-time and that the mathematical transformations of Lorentz and Einstein could be described by a rotation of a set of axes. In three-dimensional space of everyday happenings no one would be impertinent enough to say that there is any *absolute* direction of up and down, i.e., the vertical, at any one place on the earth's surface, although there are great numbers of people who believe that

New York City occupies a specially important place on the top of the world. The words "sooner or later" are likewise relative terms only and not absolute. We are all familiar with the mental process of assuming a set of three rectangular axes relating to the particular location of the observer on the earth's surface, a set, therefore, of relative coordinates, not absolute ones. If we make a section by a plane of three-dimensional space, we derive a two-dimensional space, a plane. Similarly, if a section is made through the four-dimensional world of events, a three-dimensional space will result. For an observer on the earth, there is one particular section only which will give the space of three dimensions with which he is familiar, so that the four-dimensional unity thus breaks up for him into space and ordinary time. A section through an observer on Mars would be unreal to us and unnatural in aspect. One of the postulates regarding four-dimensional space is that it must be entirely independent of the observer so that there cannot be any real difference between any two directions in an absolute sense. For any particular observer, as we have seen, the four-dimensional world of events may break up into ordinary space and time, but such a section would represent a particular case and not the most general solution.

We may draw a number of lines on a flat piece of paper or sheet of rubber. These lines intersect in many points. By taking the sheet of rubber into our hands and altering its shape, the lines on its surface become curves in three-dimensional space. A skillful mathematician could represent these curves by complicated equations of transformations involving x, y and z. By altering the shape of the piece of rubber we change the appearance of the lines on its surface, but we do not in the least change the number of the intersections made by the lines. The transformations expressing the intersection of two lines may vary greatly in their mathematical forms, but if they are true formulas, they cannot alter the actual intersections of the lines themselves. A simple case of change of axes of reference, a mathematical transformation, is familiar to everyone. While standing out in the rain, when no wind is blowing, one holds his um-

brella vertically over his head if he wishes to keep dry. The rain-drops, obeying the law of gravitation, seem to fall vertically. If the observer starts to walk, the direction of the falling rain appears to have changed, the rain-drops come in a slanting direction. Of course, the direction has not actually changed, but the effect is just the same as if there had been a real change in the direction of gravity. Some obstinate person will say that he *knows* that gravity is acting in a vertical direction and that his motion has nothing at all to do with gravity. Under this assumption he persists in holding the handle of his umbrella vertical, for he has learned that when standing at rest he keeps dry by so doing. If he still insists in his foolishness when going at high speed in a swift-moving, open automobile, he will lose his umbrella and get dripping wet into the bargain.

In four-dimensional space the " world-lines " intersect in a series of events. For the description of the world-line we can choose any set of four-dimensional axes we wish. The event takes place, however, absolutely independently of any assumption of reference axes. If we change the axes, we at the same time change the coordinates with respect to these axes, but the interesting thing is the event and not the particular set of reference axes assumed. The world of nature is made known to us only through a series of observations or series of events. We learn, in fact, only through a series of coincidences. To represent the laws of nature our observations must be true no matter what selection we make of reference axes. In other words, the mathematical expression of the laws of nature must be such that their form does not change if we make a transformation of axes.

It is a curious fact that we know very little of the mechanism by which gravitation works. Is it propagated with the velocity of light, or does it act instantaneously at infinite speed? At a place on the earth's surface, gravity is the resultant of two forces, one the attraction of the earth, the other due to the centrifugal force of the earth's rotation. The former is spoken of generally as a " natural " force, the latter as an " artificial " one. Centrifugal force may be altered by taking different locations on the surface of the earth or may be made to vanish entirely by going to the north or south poles. For the purpose of simplicity in the mathematical treatment, centrifugal force is separated from gravity. We have no direct sensation for either force separately, and in fact there is no physical basis for the separation. So why not consider the " natural " and the " artificial " force on the same basis? The generalization of this notion led to Einstein's *principle of equivalence* that a gravitational field of force is precisely equivalent to an artificial field of force, so that it is impossible by any conceivable experiment to distinguish between them. Force, therefore, is relative and not absolute.

Guided by the two principles of relativity and equivalence, Einstein was led to assume that all gravitational fields of force must be illusions. He himself admits that he was brought to his new point of view by discussing the sensations of falling with a man who had just tumbled from a high building. No distinct consciousness of falling was actually experienced by the man. The simplest method after all for the consideration of gravitation may actually be the point of view of the falling man who was experiencing no peculiar sensations of his sudden flight. This was Einstein's method. The earth was surely rising to meet the man, and if he had not known of the sudden stoppage of his flight that was in store for him, he might have quietly theorized regarding the relativity of motion. Such an unconstrained body (as the falling man) if left to itself takes what we shall call a " straight " line, but which is actually a geodesic. The world-line is undeflected until the particle of matter comes into the vicinity of another particle. The world-line of each particle is bent in towards each other or deformed. A change of direction of the particle means that a field of force has been entered. Such a deformation can be brought into the equations by means of mathematical transformations.

Gravitation therefore needs no special treatment different from that of any other force. In developing the mathematical analysis it was not possible to follow the geometry of the flat space of Euclid where the straight line is the

shortest distance between two points. The mathematician will assert that there is no reason to assume Euclidian geometry unless observation demands it. In the process of the difficult mathematical development, Einstein was at liberty to choose between several possibilities, and the decision reached seemed to give the simplest solution. In the final analysis his law of gravitation must produce the same effect as Newton's law for conditions of velocities small compared with that of light.

According to Einstein's views, gravitation is simply a geometrical deformation of unrestrained bodies, and hence we may regard the gravitational field as influencing or even determining the laws of space-time derived from measurements. The track of a ray of light therefore is deformed by the gravitational field. According to Eddington[1] " a ray of light passing near a heavy particle will be bent, firstly, owing to the non-Euclidian character of the combination of time with space. This bending is equivalent to that due to the Newtonian gravitation, and may be calculated in the ordinary way on the assumption that light has weight like a material body. Secondly, it will be bent owing to the non-Euclidian character of space alone, and this curvature is additional to that predicted by Newton's law. If then we can observe the amount of curvature of a ray of light, we can make a crucial test of whether Einstein's or Newton's theory is obeyed.

" This separation of the attraction into two parts is useful in a comparison of the new theory with the old, but from the point of view of relativity it is artificial. Our view is that light is bent in just the same manner as the track of a material particle moving with the same velocity would be bent. Both causes of bending may be ascribed either to weight or to non-Euclidian space-time, according to the nomenclature preferred. The only difference between the predictions of the old and new theories is that in one case the weight is calculated according to Newton's law of gravitation, in the other case according to Einstein's."

It has been repeatedly urged by many writers that Newton's law is simpler than Einstein's. The former is indeed more familiar, but that does not necessarily mean that it is simpler. This depends on the point of view. The principle of relativity introduced into scientific thought, first destroyed the notion that space and time were absolute in character or objective in existence. This led to a consideration of the four-dimensional world of events and to the supposition that gravitational force is an illusion. To explain this " force " as an inherent curvature in space represents a further revolution in scientific thought. Gravitation is not the only " force " familiar to the physicist. Are these also illusions and must not the Einstein theory be generalized to include all of them? Such a generalization has been proposed by Weyl who of necessity was forced to introduce new curvatures in the four-dimensional space to represent the forces involved; in fact, the effects predicted by Weyl agree so perfectly with electromagnetic theory that no testing of the theory by experiment is possible. The only scientific test to which all theories and laws must submit is the fundamental one of whether they represent the observed facts. Einstein has not attempted an explanation of gravitation other than to assume that it is propagated with the velocity of light; he has only been occupied with the deduction of its laws. Undoubtedly his theory is not in its final form but will undergo modifications as further knowledge is derived.

[1] *Space, Time and Gravitation*, p. 106.

CHAPTER XXI

HAS THE EINSTEIN THEORY BEEN COMPLETELY VERIFIED?

IF the path of a ray of light is identical with that of a material particle when passing close to a body of heavy mass like the sun, it is easy to see that the path will not be straight but will be a hyperbola. To calculate the amount of the deflection from the straight line course one might apply Newton's law; but according to Einstein's theory, this old and well established law is applicable only under the condition of small velocities. For an object traveling with the velocity of light, the Einstein formula gives a deflection twice that deduced from Newton's law.

Other important consequences follow as a direct result of the Einstein theory. According to the inverse-square law of gravitation, an isolated planet will describe about the sun an ellipse the direction of whose axis is fixed in space, but according to the Einstein law the path will be a spiral and not an ellipse. The direction of the major axis will therefore rotate in space instead of being stationary. The amount of rotation, calculated from the Einstein theory and derived without the introduction of any additional constants into the equations, is 42″ per century for the planet Mercury.

A further consequence is found when comparing the time of vibration of an atom acting under the strong gravitational pull of the sun with that of a similar atom in a terrestrial laboratory. The atom in its vibrations always behaves very much like the pendulum of an ideal clock. Since the gravitational field of force is similar in its properties to that of a centrifugal field, it is comparatively easy to calculate the effect of the theory of relativity on the vibrations of light under the gravitational action of the sun. It has

LICK OBSERVATORY CAMERA FOR TESTING THE EINSTEIN EFFECT, AUSTRALIA, 1922

been found, in virtue of this theory, that the wave-lengths at the solar surface should be greater than those under terrestrial conditions in the ration of 1.00000212:1. Each line in the solar spectrum should be shifted towards greater wave-lengths, or towards the red end of the spectrum, by an amount readily calculable. The shift at the F or Hβ line in the blue-green part of the solar spectrum should amount to 0.010 A, or one-hundreth of an angstrom.

There is a fourth consequence of the Einstein theory. If a massive particle is placed near the center of a circle and if the length of the circumference and the length of the diameter are accurately measured, it should be found that these two lengths will not be in the ratio of the famous number π. The experiment can hardly be regarded as a crucial one for testing the Einstein theory for the reason that a weight of five tons placed inside a circle of five yards radius would not change the value of π by more than one figure in the 25th place of decimals.

The astronomers at the eclipse of 1919 observed deflections in the rays of light from the stars in the neighborhood of the sun apparently in complete harmony with the prediction of Einstein. As already stated, the amount of bending predicted was 1″.75 for a beam just grazing the edge of the sun. Was the observed deflection an actual verification of the Einstein theory or can it be accounted for by some other agency? After eliminating deflections from all known causes, the observations must necessarily conform to one of three possibilities. First, there may be no deflections whatever in the stellar rays, light traveling in exact straight lines under all possible conditions; second, the amount may be the so-called Newtonian deflection of 0″.87; or third, it may be twice this size, as predicted by Einstein, *i.e.*, a curvature of space in the vicinity of the sun causing a bending of a light ray equal in amount to that demanded by the Newtonian theory. There are other deflections possible, but they need not be considered in the present status of the scientific theory.

Several books and articles have recently been written claiming that the gravitational pull of the sun has absolutely

no effect on a beam of light. The authors confidently state that observation has abundantly verified the conclusion that light travels always in perfect straight lines and hence a deflection of light rays by the sun is impossible. The brave, or possibly foolhardy, writers apparently have failed to realize that with one fell swoop they utterly disregard not only the whole of the theory of relativity but at the same time they deny that light has weight. The consequences of relativity have been so thoroughly substantiated by observations that he who has a scientific reputation at stake must indeed be very rash to state that physicists must all be mistaken and that the whole theory of relativity is " tommy-rot."

That light has weight has been thoroughly and completely verified. Clerk Maxwell showed many years ago that light is electromagnetic in character. In fact, the waves producing X-rays, photographic light, visible light, heat and wireless waves, are exactly similar in character, the only real difference being the length of the waves. The wave-lengths of X-rays are ten thousand times smaller than those of light rays while wireless waves are just as much larger. Light unquestionably possesses mass or inertia like other forms of electromagnetic energy. The tiny waves of light exert a pressure on material objects in a manner quite similar to that manifested by waves in water that pound with such terrific force on the sea shore at times of storm. The pressure exerted by light is termed light-pressure or radiation-pressure. Its consequences are described in Chapter XIX, and its effects are manifested to the astronomer in the solar corona, in the tails of comets and in the conditions in the more diffuse giant stars. This pressure exerted by light has been found experimentally in the physical laboratory. It is a consequence of the orthodox electromagnetic theory. Recent discoveries, outlined in Chapter XVI, have shown that mass is electrical in character, and consequently energy is likewise electrical, and hence light which is also electrical must possess both mass and energy. If any writer denies these conclusions, he does not by so doing destroy the scientific facts, but succeeds only in displaying his own ignorance of these facts. Even Newton himself surmised that light has weight. The admirers of the great Englishman should therefore not dogmatically deny proven scientific knowledge and state that light moves under all circumstances in straight lines even when under the strong gravitational attraction of the sun. A beam of light should therefore be deflected from its straight line course like any material particle moving with the same velocity, and hence, in interpreting the results of the eclipse photographs we must rule out the possibility that no deflection can be caused by the sun. But which is the true deflection, the Newtonian or that predicted by Einstein?

The only possible method of testing the relative merits of the two theories observationally is by means of photographing the stars surrounding the sun. On account of the glare of the daylight sky, it has been found impossible to photograph the stars in the immediate vicinity of the sun, at any time except when the sun is totally eclipsed. The amount of the deflection depends on the angular distance of the star from the sun's edge, and at a distance of one solar radius the angular deflection is but half the value at the limb. At a distance of a solar diameter, the deflection is but one-third of the limb value. The most important stars for the purpose of testing the theory are therefore those which are closest to the sun. Naturally, the brighter the star the more readily can it be photographed. What is needed for a test of the theory is a group of bright stars distributed at various angles around the sun and close to its edge. Since the sun is always found in the plane of the ecliptic, it is easy to see at a glance from a celestial chart which part of the ecliptic contains the brightest groups of stars, and then to decide at what date of the year the sun is found at this favorable position. The date turns out to be May 19. The brightest assemblage of ecliptic stars is the group known as the Hyades in the constellation of Taurus.

The British observers in 1919 were especially favored, for the eclipse occurred on the nineteenth of May. Two expeditions were dispatched. Crommelin and Davidson representing the Greenwich Observatory went to Sobral in North

Brazil, while Eddington and Cottingham from Cambridge located at the Isle of Principe in the Gulf of Guinea, West Africa. The telescope used at Principe was the thirteen-inch "astrographic" telescope belonging to the Oxford Observatory. The telescope was used horizontally, the light from the sun being reflected down the tube by a coelostat mirror. The focal length of 11 feet 4 inches insures a scale of the photographs of one millimeter equal to one minute of arc. One second of arc is thus equal to one-sixtieth of a millimeter or one-fifteenth-hundreth of an inch. In order to secure increased sharpness of the star images, the aperture of the lens was stopped down to eight inches. On eclipse day clouds greatly interfered with the progress of the work. On account of the long duration of totality amounting to six minutes, sixteen photographs were obtained with exposures ranging from 2 to 20 seconds. Unfortunately on many of the plates, one or more of the essential stars were missing on account of clouds.

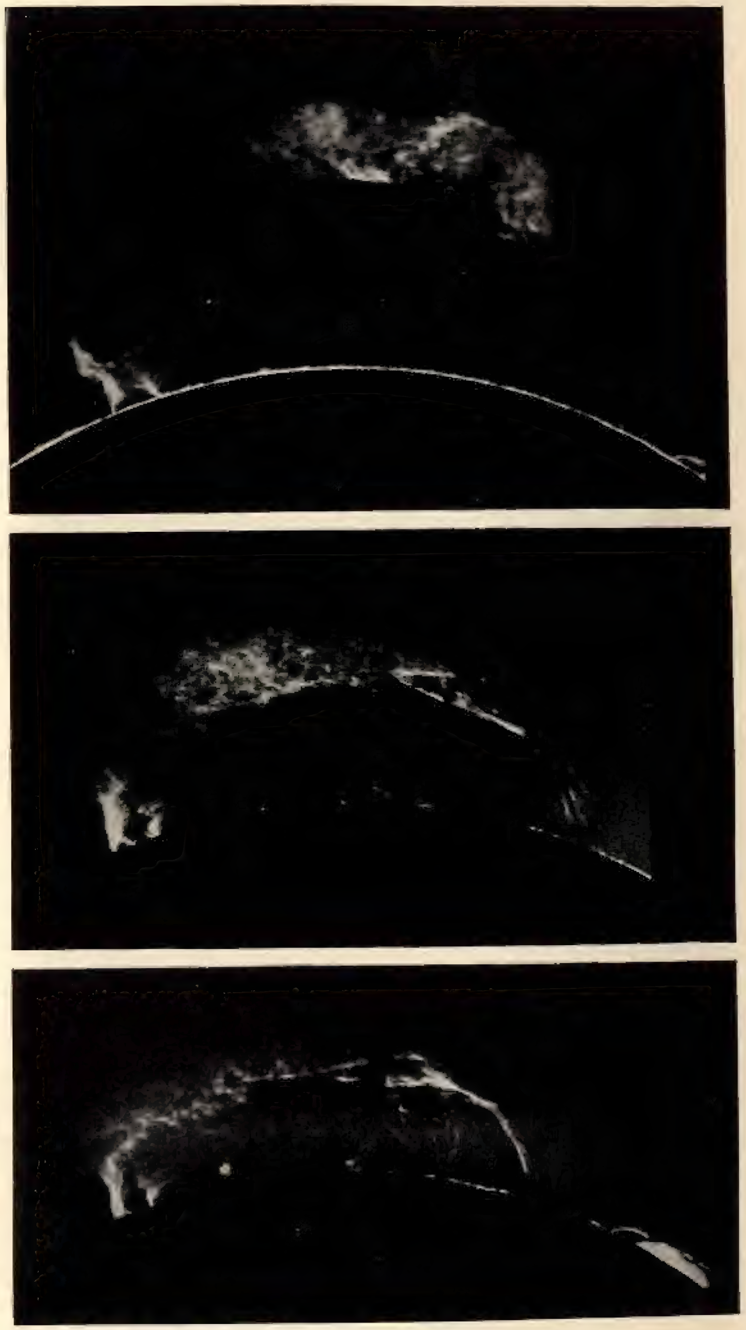
In Brazil the observers were favored with fine weather. They utilized two telescopes for securing their photographs, one similar in size to the one at Principe, the other with the greater focal length of 19 feet and aperture four inches. The photographs with the former instrument were a grave disappointment, for the star images were not in sharp focus, due unquestionably to the warping of the mirror by the heat of the sun. Seven of the plates taken with the four-inch lens were found satisfactory for measurement. Only two of the Principe plates were measured and on these the images were not particularly well-defined and moreover they were weak due to the interposing clouds. The sixteen plates secured at Sobral with the astrographic telescope were also measured in spite of their poor definition.

In order to secure from the eclipse plates results of the highest value, it is necessary to photograph as a check the same region in the sky but with the sun absent. To be of the greatest worth, the check plates thus obtained should reproduce as closely as possible the conditions under which the eclipse photographs are taken. The plates should, if possible, be taken at the site of the eclipse, and with hour

G. M. T.
$5^h\ 32^m\ 41^s$

$2^h\ 56^m\ 56^s$

$1^h\ 41^m\ 16^s$



THE GREAT PROMINENCE OF MAY 29, 1919

Photographed at Yerkes Observatory by Pettit with the Spectroheliograph on the day of the total eclipse. The greatest height attained on this day was 760,000 km.

angle, temperature, etc., of the eclipse duplicated as nearly as possible in the check photographs. Such a procedure requires a stay of two or three months at the eclipse camp, frequently located thousands of miles from home. The Principe observers indeed secured check plates, but not at Principe, but with the telescope mounted in England. The conditions of latitude and temperatures were vastly different in the two series of plates, and furthermore the plates taken in England were secured without the interposition of the mirror used at eclipse time. In view of their faulty nature as check plates, an additional precaution was taken of securing an extra series of plates photographed at Principe and in England but portraying a different stellar region, since it was found impractical to remain at Principe. The Sobral observers did remain an additional two months after the eclipse to secure the desired check plates.

Many publications giving the results of the measures of the 1919 eclipse photographs have so recently appeared that it will be unnecessary to go into details. For the final discussion, plates taken with three separate instruments are available. The values of the Einstein effect reduced to tangency to the sun's limb are:

From	7	Sobral	Plates	taken	with	4-inch	lens,	$1''.98 \pm 0''.12$
From	2	Principe	“	“	“	13 “	“	$1''.61 \pm 0''.30$
From	16	Sobral	“	“	“	13 “	“	$0''.93$

The values which follow the angles of deflection give the "probable error" familiar to all astronomers. Probable errors are derived by computation from the interagreement of the separate measures of a series, and they are generally regarded as an indication of the degree of dependability or reliability of the final results. Many confused ideas of the significance of probable errors are prevalent, and even among astronomers who ought to know better. Referring to the result above, obtained by the 4-inch lens, the probable error secured does *not* signify that the true value of the Einstein deflection must lie somewhere between $1''.98 + 0''.12$ or $2''.10$, and $1''.98 - 0''.12$ or $1''.86$. The *true* value is in fact unknown and unknowable. In all scientific work information

can be acquired solely as the result of measurements. The scientist endeavors to make his measures as precise as possible, with errors reduced to a minimum in size, but it is impossible for him ever to know the actual or true errors inherent in his work. By common consent of all English-speaking peoples, the probable error is employed to indicate the probable or possible precision of the measure.

On account of the poor definition of the sixteen plates taken with the Sobral 13-inch lens, the values of the Einstein deflection from these plates, ranging as they did from 0.″00 to 1″.28, were omitted from the final mean. Combining the two remaining series with weights depending on the probable errors, there results the deflection of 1″.93. Giving equal weight to each of the series, the value becomes 1″.80. The value predicted by Einstein is 1″.75. The observed mean value certainly gives no indication of an absence of deflection by the sun nor is the half-deflection according to the Newtonian theory shown. The close agreement between observation and prediction was received with the greatest interest and remarkable enthusiasm throughout the whole of the thinking world.

In spite of the good agreement, no one, least of all the British observers themselves, will affirm that the Einstein deflection has been completely verified by the 1919 eclipse results. For some strange line of reasoning the sixteen Sobral plates were entirely neglected. Scientific men are fully aware of the fact that errors may creep into measures no matter how carefully made. It is safe to say that the Einstein problem will find a place on eclipse programs for the next quarter of a century. The chief place of importance at the 1922 eclipse was given to this problem, and the same will be true in 1923.

The best series of the 1919 plates give a result 1″.98 ± 0″.12. This certainly does not appear to confirm the half-deflection of 0″.87, but on the other hand the poorest of the three series of plates does furnish a value closely agreeing with the Newtonian deflection. The remaining value, 1″.61 ± 0″.30, although it agrees closely with the full deflection, might, on account of the size of the probable error, possibly confirm the half amount. Furthermore the plates taken at the 1918 eclipse by the Lick Observatory with the five-inch and forty-feet-focus camera pointed directly at the sun gave no indication of any appreciable bending.

The results obtained in 1919 were pioneer in character; and improvements over the methods followed are readily apparent. First, the coelostat mirrors must be eliminated by mounting the cameras on an equatorial mounting and pointing the lenses directly at the sun. Not only do the mirrors prevent a maintenance of constant focus, on account of the warping of their surfaces by the heat of the sun, but the mirrors may introduce distortions in the photographs. As Russell, Slocum and others have shown, evidences of such distortions are seen in the published results of the British observers. Work at future eclipses demands that check plates must certainly be secured and under conditions resembling as closely as possible those of the day of the eclipse.

It must not be thought that the amount of the deflection caused by the sun is an angle so minute in size that its measurement will tax the resources of modern astronomy. In determining the distances of the fixed stars, parallax observers are quite used to measuring displacements on their photographic plates many times smaller in size than the Einstein deflection by the sun. There are half a dozen of the observatories in the United States alone which are devoting much of their energies to parallax determinations. Nor does the problem of measuring the eclipse plates contain anything startlingly new in the method. Astronomers for many years are quite familiar with all of the processes involved in the measurements and reductions, and moreover they are quite accustomed to securing an accuracy much greater than that demanded by the Einstein problem. In regular observatory work, such as required in the determination of the parallax of the stars, astronomers are confident that constancy of results can be expected from night to night in photographs taken with the telescope, and they have long series of observations to prove their conclusions; in fact, in parallax determinations an accuracy is secured

which is measured by a probable error one two-hundredth part of the maximum deflection demanded by the Einstein theory.

If a total eclipse took place every day, the astronomer would have abundant opportunity to vary the observing conditions and thoroughly eliminate all possible sources of error, but with eclipses occurring so seldom he must do the best he can under unusual conditions. The check photographs are secured for this purpose. The scale of the photographs, the orientation and the various correcting factors that must be taken into account in the reductions are obtained from the check photographs. If these plates are photographed *through* the glass, which is possible by the use of plate glass, then the eclipse plates and the check plates may be placed film to film and the star images on the eclipse plates will nearly match in position those of the check plates. The measurement thus becomes a differential one of comparing the stars on the eclipse plate, image by image, with those of the check plates. The method of reduction makes due allowance for any changes in scale-value, orientation, refraction, etc., and we can confidently expect that the gravitational deflection will be readily separated from all other effects, provided care is taken in securing a satisfactory series of plates to act as checks. Before discussing the results of the 1922 eclipse we must survey the other consequences of the Einstein theory.

Of the eight major members of the solar system, Mercury is the exceptional planet. It is closest to the sun and has the greatest orbital motion, it has the smallest mass, its orbit has the greatest eccentricity and is inclined by the greatest angle to the ecliptic. Mainly on account of the great eccentricity and high inclination, the path of the planet has caused considerable worry to the mathematical astronomer. Mercury is never seen more than 28° from the sun and it is therefore only visible to the naked eye shortly after sunset or before sunrise projected on a strong twilight sky. With a telescope, however, the planet may be observed in the daylight sky. Tables of motion of Mercury were made by Kepler as early as 1627, by Halley about 1680 and by Lalande a hundred years later. The first really accurate tables were those of Leverrier based on meridian observations made at the Paris Observatory between the years 1801 and 1842, and supplemented by observations of transits of the planet across the face of the sun beginning with that of 1631. Leverrier discussed the observations in a thoroughly masterful manner, calculating the gravitational attractions of the other planets for Mercury whereby the orbit was perturbed. It was found by him that the observed motion of the axis of the planet's ellipse was moving 0″.38 per year, or 38″ per century, in excess of the amount calculated from the law of gravitation.

Leverrier discovered several possible reasons for the discrepancy, the most plausible being the presence of a planet, or group of planets, between the orbit of Mercury and the sun. On March 26, 1859, Lescarbault observed such a planet in transit across the face of the sun. It was found later that Lescarbault's planet did not follow the orbit calculated for it by its discoverer and that the transits predicted by him failed to materialize. Unquestionably, the original observation and those of many additional transits of other planets supposed to have been seen by others find a ready explanation in the appearance of spots on the face of the sun. The discovery of two intra-Mercurial planets at the eclipse of 1878 (*see* Chapter IX) has likewise never been verified.

Two decades after Leverrier had completed his work, the same problem was attacked by Simon Newcomb; and naturally with much more material to his hands than was available earlier. No less than 5421 observations of Mercury entered into the discussion, and a total of over sixty thousand into the research on the motions of the four inner planets, Mercury, Venus, Earth and Mars.

The observed motion of the perihelion of Mercury deduced by Newcomb was 41″.6 ± 1″.4 in excess of that calculated from the law of gravitation. Such a large discrepancy appearing in Mercury, what of the other planets? The orbit of Venus is really too nearly circular to permit of the observation of the direction of the major axis of its orbit

with accuracy and the same is true, but in lesser degree, for the earth. The values of the motions were calculated but the precision of the results for Venus and Earth were inferior to those of Mercury and Mars. This latter planet with its greater eccentricity of orbit shows an unexplained discrepancy of 8″.1 in the motion of its perihelion.

According to Einstein's law of gravitation, the planetary orbits not being closed ellipses but spirals, the path is slightly advanced at each revolution in the direction of the motion of the planet. The prediction of Einstein gives a simple formula, namely, that the orbit of any planet will advance through a fraction of a revolution measured by $3v^2 / c^2$, where v is the velocity of the planet and c the velocity of light. The values of v for each of the planets is known with great exactness. For the four inner planets, the Einstein motions per century are: 42″.9 for Mercury, 8″.6 for Venus, 3″.8 for the Earth and 1″.3 for Mars; showing a remarkable agreement for Mercury but little improvement in the discrepancy of Mars. Further disagreements between observation and motion calculated on the Newtonian theory were found by Newcomb, the most important being 10″.2 in the node of Venus and 0″.88 in the eccentricity of Mercury. The Einstein theory does not apply to the two last discordances. Attention should thus be called to the fact that the motion of the perihelion of Mercury is not the only wide divergence from the law of gravitation found in the discussion of the motions of the planets. Its value is the largest, it is true, but the other disagreements are none the less important in spite of their smaller size.

Before we can accept the Einstein theory as the true explanation of the motion of the perihelion of Mercury, we must first exhaust all other explanations arising from the Newtonian law of gravitation, and all possible deflections in the photographs caused by refraction, etc. If the unexplained motion of the perihelion had been Leverrier's 38″ instead of Newcomb's 42″, the Einstein prediction of 43″ would hardly have been received with the universal acclaim accorded the almost perfect agreement. Newcomb, many years ago showed that the motion of Mercury can be completely accounted for under several hypotheses, but unfortunately in explaining away the discordance in Mercury's motion, discordances were introduced into the other planets so that the last state appeared no better than the first. There are three possibilities:

(1) A non-spherical sun
(2) A ring of matter surrounding the sun
(3) The number 2 in Newton's law is only a first approximation.

According to Charles Lane Poor,[1] " the ordinary classical methods of physical and astronomical research can fully explain all of the observed phenomena; the motions of the planets can be fully accounted for by the presence of matter known to exist, and the light deflection, if real, can be explained as the result of refraction through the cosmic dust surrounding the sun."

It was shown by Poor that if the equatorial diameter of the sun exceeds the polar diameter by an angle of 0″.10, it will cause a motion of the perihelion of Mercury amounting to but 7″ per century. Although from theoretical grounds the rotation of the sun should cause a bulging of the sun at the equator, such an effect has never been detected with certainty (*see* Chapter VII). The excess of equatorial diameter of the sun can hardly amount to more than 0″.05, and this would affect the orbit of Mercury but little.

It was next shown by Poor that the assumption of a lens-shaped material appendage surrounding the sun will be sufficient to explain not only the motion of Mercury, but practically all of the other divergences from the law of gravitation as well. The method adopted by him was one very familiar in practice, namely, that of introducing as many constants into the calculation as there are quantities to be allowed for. In the solar corona there is evidence of an appendage to the sun, and furthermore, the zodiacal light gives an indication of an envelope stretching out from the sun vastly farther than the corona. The corona is more or less symmetrical with respect to the sun's equator, while the

[1] *Gravitation versus Relativity*, 227, 1922.

plane of the zodiacal light is that of the earth's orbit. For the purpose of simplicity of computation, Poor assumed the entire mass surrounding the sun to be made up of three superimposed ellipsoids, each of constant density, as follows:

a. A small central ellipsoid entirely within the orbit of Mercury.

b. An intermediate ellipsoid entirely within the orbit of the Earth, but extending beyond the orbit of Venus.

c. An outer ellipsoid within the orbit of Mars, but extending beyond the orbit of the Earth.

It is evident that the larger the radius of the assumed ellipsoid the smaller the mass that ellipsoid must contain in order to account for the motions. By arbitrarily assuming definite radii for three assumed ellipsoids, the corresponding masses and densities of the material may be derived. The plane of the inner ellipsoid was chosen so as to explain the discordances in the motions as completely as possible, while the planes of the two other ellipsoids were assumed to coincide with the orbit of Jupiter. The computations may be carried out according to the familiar formulas of celestial mechanics. Assuming that the inner ellipsoid extended 20 diameters of the sun, or about half the distance to Mercury, and the intermediate ellipsoid to be a trifle smaller than the orbit of the earth, Poor calculated the masses compared with the mass of Mercury, and densities referred to atmospheric pressure, and with the following results:

	Mass	Density
Inner ellipsoid	3	8.9×10^{-8}
Intermediate ellipsoid	4/7	1.3×10^{-10}

According to Poor (*loc. cit.* p. 237), "there is apparently no mechanical nor physical reason for the non-existence of a group, or groups, of bodies, sufficient to explain all the irregularities in the motions of the planets. Thus, all the discordances, including that of the perihelion of Mercury, can readily be accounted for by the action, under the Newtonian law, of matter known to be in the immediate vicinity of the sun and planets." Such a distribution of material would cause a true atmosphere surrounding the sun which would not be of the uniform density (assumed for ease in computation), but which would be very dense close to the sun's surface.

An atmosphere of this character would cause refraction on a beam of light when it passed through this atmosphere. In fact, Poor assumes that such a refraction is a sufficient cause to explain the whole of the bending of the rays of light at the 1919 eclipse. On the other hand, Eddington[1] shows that "at a height of 400,000 miles above the surface of the sun the refractive index required is 1.0000021. This corresponds to air at $\frac{1}{140}$ atmosphere, hydrogen at $\frac{1}{70}$ atmosphere, helium at $\frac{1}{20}$ atmospheric pressure. It seems obvious that there can be no material of this order of density at such a distance from the sun. If there were, the pressure on the sun's surface of the columns of material involved would be of the order of 10,000 atmospheres; and we know from spectroscopic evidence that there is no pressure of this order."

Dr. Harold Jeffreys[2] discussed the effect, on the perihelion of Mercury and on the shifting of star places, of matter known to be in the immediate vicinity of the sun and planets, namely the solar corona and the zodiacal light, in the following manner: "You can determine the density perfectly from the luminosity. You know the intensity of light that falls on these masses; you know the distance; you have a fair idea of the physical constitution; and you need simply compare these with the light that you receive from the sky at midday to get a direct estimate of the amount of these two deflections that can be got from this mass that is known to exist. The results are rather startling. There is enough matter in the zodiacal light to account for one three-thousandth of the motion of the perihelion of Mercury. There is enough matter in the corona to account for about 10^{-8} of the motion of the perihelion of Mercury. The solar corona, by means of its refraction, is capable of producing one-millionth of the observed deflection of the

[1] *Space, Time and Gravitation,* p. 121.
[2] *Monthly Notices, R. A. S. 80.* 116, 138, 1919.

star images. So I think it is clear that the only reasonable interpretation one can make of these two shifts is that they are due to some property of the law of gravitation."

Another method of explaining the motion of Mercury under Newton's law was that suggested many years ago by Hall. If the exponent 2 in the inverse square law is increased until it becomes 2.00000016, then the effect on the perihelia of the inner planets as computed by Newcomb becomes: Mercury 43″.37, Venus 16″.98, Earth 10″.45 and Mars 5″.55. While the values of Mercury and Mars agree well with the observed displacements, those of Venus and the Earth are very wide of the true values.

Of the utmost importance to the Einstein theory is the accurate determination of the shift of the spectral lines in the sun towards the red when the wave-lengths are compared with those derived under terrestrial conditions. If the lines of the spectrum had the elemental character supposed to exist by the discoverer of the laws of spectrum analysis, Kirchhoff, the problem would be one of great simplicity for the reason that the Einstein shift is comparatively large, 0.010 A in the blue-green part of the spectrum. With the superb equipment at the Mt. Wilson Observatory it has been possible to detect the general magnetic field of the sun by measuring the shift in certain spectral lines from the Zeeman effect amounting to only 0.001 A (*see* Chapter XV), or one-tenth the amount of the relativity displacement.

The problem seems at first sight to admit of a ready solution. If the wave-lengths of the arc spectrum are determined in the laboratory with the highest degree of precision attainable and these are directly compared with solar wave-lengths, the difference in the values should give the required displacement, *provided* allowance is made for all known effects that can alter the wave-lengths both in the laboratory and in the sun. Unfortunately, in addition to the known causes that shift the spectral lines, there are many effects that produce displacements of unknown amounts. Apart from instrumental defects, the chief causes of the displacement of solar lines, in addition to the relativ-

SAILORS OF THE AUSTRALIAN NAVY ASSISTING THEIR BROTHERS FROM CANADA IN ERECTING THE EINSTEIN CAMERA

ity effect, may be due to the following factors, most of which have been discussed in detail in Chapters XIV and XV: (*a*) Motion in the line of sight, (*b*) Pressure effects, (*c*) Anomalous dispersion, (*d*) Lines of different intensities originate at different levels, (*e*) Influence of neighboring spectral lines upon one another, etc. Various causes alter the wave-lengths of the arc spectrum, chief among which are pole effects, and Zeeman and Stark effects. The wave-lengths emitted by the different parts of the electric arc, in fact, are found to be very discordant. The displacements are always larger at the negative pole of the arc. For the sodium pair at 6154 A and 6160 A, for instance, the displacement under certain conditions may amount to 0.52 A.

In addition to the arc displacements, which at times may amount to many times the value of the relativity shift, it is unfortunate that so little is known of the conditions in the solar atmosphere. In determining the sun-arc displacements, it is necessary to make certain assumptions regarding the effects of pressure, etc., and after making due allowance for all possible sources of shifts, the balance left over is assumed to represent the prediction of Einstein. In view of the work of Rossi, that the cyanogen band at 3883 A is little affected by pressures up to 100 atmospheres, many investigations have been carried out on this promising region. The unsatisfactory nature of the conclusions have been summarized in the *Annual Report of the Director of the Mt. Wilson Observatory*, 1921, p. 242, in part as follows: From the line 4197, the unsymmetrical head of the second band, Pérot, after applying a correction for an assumed *downward* movement in the solar atmosphere and for a *negative* pressure shift of the cyanogen-band lines, the latter approximately equal in magnitude to the shift required by relativity, finds that the sun-arc displacement is that predicted by the theory. On the other hand, Birge, after applying a correction for an *upward* movement and assuming *no* pressure shift for the band lines, finds two lines which he considers free from the superposed lines of other series and which give displacements approximately equal to those required by the

relativity hypothesis. Greve and Bachem start out with different assumptions from those of Pérot and Birge, and assume *no* motion of the solar vapors and *no* pressure shift for the band lines, but apply a correction not employed by the two other investigators for a supposed *asymmetry* of the arc lines; and moreover they too verified the Einstein effect.

Investigations at Mt. Wilson show that although the shift of the lines of the cyanogen band through pressure is small, nevertheless it amounts to 0.0001 A per atmosphere. Further investigations proved that "in view of the superposition of lines, of the changes in relative intensity with temperature, and of the line-density in the solar spectrum, it appears that the cyanogen band is not well adapted for a definite test of the theory." Equally inconclusive are the results obtained from the magnesium line at 5172 A.

When one refers to the widely different values of the solar rotation obtained as the result of an extended series of most careful and refined measures carried out by the most skillful of the world's solar spectroscopists, one glimpses, as in Chapter XV, some of the difficulties of the problem. The verification of the Einstein prediction by sun-arc displacements is even a more difficult task than that of measuring the solar rotation by spectroscopic methods. The relativity shift certainly cannot be determined by measuring a few lines and making plausible assumptions regarding pressures and various other effects. To reach a definite conclusion it will manifestly be necessary to carry out a much more extensive program of work, both on the sun and in the laboratory. The goal of such work is indeed the determination of a satisfactory system of arc and solar wave-lengths each reduced to the *international standard,* and with the wave-lengths in sun and arc freed as much as possible from possible sources of errors. Such investigations demand the most refined instrumental equipment and specialized training of the highest order that can come only from long years of practical research.

At the present time (1923), the prediction from the Einstein theory that the lines in the solar spectrum are shifted towards the red compared with terrestrial standards has

certainly not been verified. We look to the Mt. Wilson and Kodaikanal Observatories to continue their attacks on this vital and interesting problem, being confident that the evidence will be carefully sifted, and the truth, and nothing but the truth, will finally prevail.

Since the first burst of enthusiasm in 1919, following the measures made by the British astronomers at the total eclipse of that year, scientists have had a chance to examine more fully into the theory of the bending of the light of a star when the stellar beam passes close to the sun. The problem is after all not a novel one in scientific thought, but dates back more than one hundred years to the celebrated English physicist Cavendish who calculated, on the basis of the corpuscular theory, the amount that the corpuscles of light are bent towards the sun in passing it. As long ago as 1801, Dr. J. von Soldner derived formulas, which were published in Bode's *Astron. Jahrbuch* for 1804, from which the deflection of light at the edge of the sun on the corpuscular theory was computed to be 0.″84. (Using modern values of the astronomical constants, this value is changed to 0.″87.)

It is passing strange that in the many writings by Einstein no mention is made of the work of von Soldner. It is even claimed by Professor P. Leonard of Heidelberg that von Soldner made a mistake in his original writings whereby a certain factor was omitted and that the same error, uncorrected, is found in Einstein's publications.

Although it is quite possible that Einstein knew of these earlier contributions and failed to give due credit to their authors, these attacks on him — accusing him of plagiarism — cannot greatly detract from the merit due him on account of his splendid development of the general theory of relativity.

It should be clearly borne in mind, however, that in the progress of the mathematical treatment by him the equations became very complicated; and for the sake of simplicity, of securing a set of equations that could be manipulated, it was necessary to make certain assumptions. The theory coming from his hands is therefore not in its most

generalized form, and it is true only in so far as the restrictions imposed by the selection of the set of hypotheses can represent the observed facts. These limitations curtail the applicability of the theory, — but the method, rendered necessary for the purpose of securing results, is almost as old as science itself.

Two great difficulties present themselves to the average mind when attempting to grasp the meaning of the Einstein theory. The first of these two is that it is almost impossible to conceive that the coordinate time differs in no essential particulars from the three dimensions of length, breadth and thickness. The upholders of the relativity theory assert that the world of events is rendered the simpler by this consideration of a space-time concept of four dimensions, even though it is necessary, as a consequence, to regard the whole volume of space as finite, but nevertheless without a boundary. As a matter of fact, no one can possibly picture the curvature of a four-dimensional continuum for the reason that there is nothing at all in our experience comparable with it.

There are some individuals with mathematically trained minds who have persuaded themselves that they can really grasp the conception of the four-dimensional world of space-time; but most of these rebel and refuse to be convinced when, as a second consequence of the Einstein theory, it is necessary to assume that gravitation should receive no treatment different from that accorded the other " forces " of nature. Gravitation is therefore *explained* by Einstein as being due to the curvature of space and time. Certain master minds, like Eddington,[1] state that a great simplification has taken place; and that " we have realized for the first time that a world without gravitation (without curvature) would be more specialized and stand more in need of explanation than the actual world disturbed by gravitation."

Eddington's colleague at Cambridge, Sir Joseph Larmor,[2] finds difficulty in believing that " the world of so-called classical physical science is an illusion, an imperfect picture of a

[1] *Scientia,* 33, 313, 1923.
[2] *Phil. Mag.* 45, 243, 1923.

reality depending symbolically on a field of fourfold quasi-geometrical algebra, of a presumed cosmos deep below the sensual sources of our concrete physical knowledge, of which we may obtain shadowy glimpses, but which is as yet quite beyond any direct grasp or intuition." Furthermore, in this important paper (*loc. cit.*) Larmor states the belief that the *principle of equivalence* between a field of gravitation and a field of acceleration seems definitely to have failed. Larmor makes a careful study of the whole problem and comes to the definite conclusion (derived before the date of the 1922 eclipse) that the maximum deflection experienced by the stars surrounding the sun at an eclipse should amount to one-half that predicted by the Einstein theory, or in other words, 0″.87 at the limb of the sun.

Thus at the present time (1923) there seems to be no pronounced unanimity of opinion among mathematical physicists of the most advanced type. When the astronomers have become fully agreed upon the size of the deflection at the limb of the sun actually observed at the time of a total eclipse, it will perhaps be easier for the physicists to agree more thoroughly among themselves on the points of controversy included in the relativity theory.

The eclipse of 1919 certainly did not furnish a decisive answer regarding the verification of the Einstein problem. The work at best was pioneer in its nature, but it did give invaluable information regarding the best method of procedure for researches of the future. At the eclipse of 1922, four improvements over the methods adopted in 1919 were incorporated. First, the coelostat mirrors were eliminated, the cameras being pointed directly at the sun. Second, the lenses employed were quadruple, and not the ordinary achromatic combination of flint and crown glass lenses; thus ensuring a flat field over a very large area. Third, instead of trusting to luck that the driving mechanism would perform its duties perfectly, auxiliary guiding on a star during the eclipse exposures was attempted. Fourth, the securing of check plates was thoroughly accomplished.

The observers devoting themselves mainly to the Einstein problem were the British party of Jones and Melotte who

located on Christmas Island in the Indian Ocean, and a combined German-Dutch expedition with headquarters also on Christmas Island. In Northwest Australia was the Lick-Crocker expedition under the direction of Dr. W. W. Campbell, a Canadian party from the University of Toronto consisting of Dr. C. A. Chant and Dr. R. K. Young, and Mr. J. Evershed from the Kodiakanal Observatory of India.

The British observers at Christmas Island spent six months at the eclipse site in order to secure the check plates in advance of the eclipse and also that photographs might be secured of the southern skies to be used for measuring the magnitudes of the southern stars. The observers unfortunately found conditions nearly identical with those experienced in Sumatra at the eclipse of 1901. The skies were so covered with thin haze or heavier clouds almost every night that neither the check plates nor the other stellar photographs so much desired could be secured. To add to the continued disappointment of the observers, the sky was clouded during the critical minutes on September 21 and no eclipse photographs were secured either by the English or by the German-Dutch parties.

The Einstein equipment of the Lick Observatory party consisted of one pair of lenses each of 5 inches aperture and 15 feet in focal length, and another pair of four inches aperture and 5 feet in focal length. Each lens was a quadruplet and the specifications required a flat field giving gold star images over plates 17 x 17 inches. The photographic films were coated on plate glass a quarter of an inch in thickness.

Wallal, the headquarters of a sheep ranch on the bleak shores of Northwest Australia, was chosen as the scene of operations by the Lick and Canadian observers. It was found not to be practicable to send an observer with the Einstein cameras to Wallal three months or more before the eclipse in order to mount and adjust the cameras and secure the necessary check plates in the night skies, and consequently it was decided that Trumpler should secure these plates in Tahiti in the Southern Pacific where the living conditions were more kindly. The latitude of Tahiti

(17° 32′ S) differed little from that of Wallal (19° 45′ S) and it was thought that the temperatures at night at Tahiti would differ little from those by day at Wallal. Dr. Trumpler, in spite of much interference from clouds, secured the necessary plates, not only with each of the four Lick objectives but with the two Canadian cameras as well.

As an extra precaution, it was decided to photograph on each plate taken at Tahiti not only the critical star group where the sun would be projected at the time of the eclipse, but also an auxiliary group having the same declination but with a right ascension six hours farther east. The night before the eclipse, the photographic plates to be used for the first half of the eclipse set were exposed to the auxiliary group, while the second half of the eclipse plates were exposed to the star group at night following the eclipse. The use of the second star group thus furnished a double check on the accuracy of the eclipse photographs and by their means it was hoped completely to eliminate any systematic errors that might possibly creep into the Tahiti plates because of their not having been actually taken at the eclipse site.

The Australian government set a high standard of scientific cooperation. All eclipse observers were carried by railroad free of charge from Sydney to Freemantle and return. They were transported by ship from Freemantle to Broome and then to Wallal and return. The heavy equipment, weighing about thirty-five tons, was landed on the beach and transferred a mile and a half inland to the observing camp. The labor needed for this and for most of the operations required by nearly a month's stay at Wallal, including complete sleeping and dining service, was rendered entirely gratis. In the estimation of Director Campbell[1] "the hospitality extended, the interest shown, and the assistance offered, were of a standard higher than I have ever observed in any other part of the world on any occasion."

The population of whites in the Wallal region numbered only six persons. Many serious obstacles had to be overcome in the short time available before the instruments

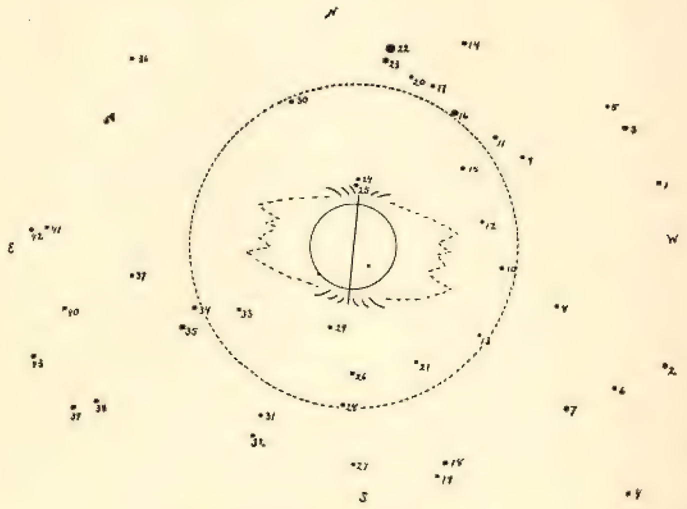
[1] *Publ. A. S. P.*, *35*, 11, 1923.

were erected and accurately adjusted. Perhaps the greatest trials were the dust and the flies. The eclipse site was in the bed of an extinct lake, and on account of the small annual rainfall the ground was very dry and a cloud of fine dust was raised at each step by a person walking, and a gentle wind carried it to all portions of the plate holders and optical parts of the delicate apparatus. In order to attempt to keep down the dust, five blacks were continuously employed throughout the whole stay carrying coarse sand and distributing it on the ground surrounding the instruments. On the morning of eclipse day, September 21, green boughs were cut from trees and placed on the ground and water plentifully sprinkled around in order to attempt to diminish the radiation from the heated soil. Fortunately for the observers, the work of adjusting and erecting the apparatus was not interfered with by clouds. Only occasionally during the month's stay at Wallal were clouds seen and these never appeared far above the horizon.

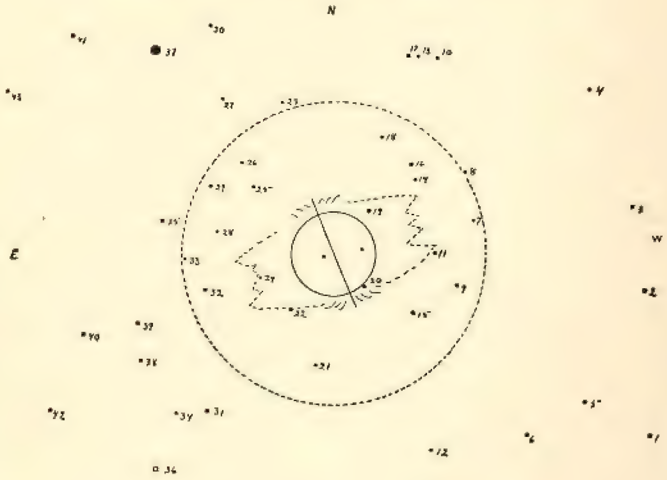
The account (*loc. cit.*) by the director of the Lick Observatory of the preparation for the eclipse gives one an inkling of the reasons why the Lick-Crocker expeditions have established such a splendid record for scientific work accomplished at eclipses. The Lick program is always carefully planned, the equipment is the very best that modern engineering can supply, the apparatus is thoroughly tested at home so that when it arrives at the eclipse site it can be readily erected and adjusted. Added to the above is the vast experience gained by the successful observations of eclipses in all quarters of the globe during the past thirty years. The author wishes to pay high tribute to his friend, the present director of the Lick Observatory and also to the friends of the observatory whose scientific interest and financial backing have made the Lick-Crocker expeditions possible.

On eclipse day, September 21, in Wallal not a single cloud was visible from morning to night, — the astronomers could not therefore lay the blame on the weather if their photographs turned out unsuccessfully.

The most important problem for this eclipse was unques-



STAR FIELD FOR THE 1925 TOTAL ECLIPSE



STAR FIELD FOR THE 1923 ECLIPSE OF THE SUN

tionably the photographs for testing the Einstein problem. The first results to be published were those of the Canadian party of Chant and Young. Their Einstein camera was a quadruplet lens of 6 inches aperture and 11 feet focal length. Two photographs were secured during totality. The two eclipse plates were compared with two check plates secured at Tahiti by Trumpler. An additional check plate was secured with the photograph taken *through the glass*. Each of the four plates was placed film to film with this fifth plate and the measures of the star positions were made by differential methods. The plates were measured at the Dominion Astrophysical Observatory at Victoria by Young and Harper independently. A description of the methods of measurement and reduction is given by Young in the *Journal of the Royal Astronomical Society of Canada, 17*, 129, 1923. On each of the eclipse plates about twenty-five star images were visible, but some of these images were so weak that accurate measurements of them were impossible. Only nineteen stars were subjected to measurement.

The scale of the plates was such that one inch was equivalent to 1560 seconds of arc and one millimeter equal to 62 seconds. Owing to the lack of accord among the measures, it is evident that the definition was not of the very best. The average of the Einstein deflections actually measured on the plates was but one two-hundredth part of a millimeter or one five-thousandth part of an inch. The first solution of the Canadian plates included eighteen star images, one star being neglected on account of little weight. Giving all stars equal weight, this solution gave for the deflection reduced to the sun's limb, 1″.38 for the first eclipse plate and 2″.09 for the second, a mean of 1″.74 for the two, though the results from the x and y coordinates were not very accordant. Three of the eighteen star images gave results much in error, two of the residuals being over 1″ of arc. Omitting all three stars, the results in x-coordinates give 1″.30 and 2″.17 for the two plates, respectively, with a mean of 1″.73 for the deflection at the limb. The mean of the y-measures (which had comparatively little weight) gave a deflection of only 0″.66. Omitting only two of the

three stars (the third star giving the largest expected displacement), the solutions for the two plates were 1″.73 and 2″.75 respectively. Combining the measures of the two plates, there is given below the results from the fifteen most accordant stars, divided into groups according as the expected displacements are greater or less than 0″.25:

EXPECTED DISPLACEMENTS GREATER THAN 0″.25

Expected	0″.48	.41	.40	.30	.28	.27
Measured	.30	.44	.28	.25	.66	.22
Red. to limb	1.08	1.89	1.23	1.45	4.09	1.43

EXPECTED DISPLACEMENTS LESS THAN 0″.25

Expected	0″.24	.24	.24	.22	.22	.21	.21	.21	.18
Measured	−.31	.12	−.11	.23	.08	.06	.53	.77	−.05

In the first group, the fifth star gives the discordant result of 4″.09. It is evident that the stars closest to the sun's edge, where the displacement is the greatest, should carry the greatest weight since the accidental errors of measurement are relatively smaller in amount. The mean of the six in the first group gives the deflection, reduced to the sun's limb, of 1″.86 while the first four give a value of 1″.41.

On account of the discordant results, it may be said that the Canadian plates give indisputable evidence of deflections of the stars' images by the sun, but these results, though being approximately of the correct size, can hardly be regarded as fully confirming the deflections demanded by the Einstein theory.

The second report published on this same problem at the 1922 eclipse was by Evershed (*Kodiakanal Bulletin,* No. 72) who used a 12-inch photovisual lens with coelostat mirror. The site selected was at Wallal close to the Lick and Canadian parties. Owing to the apparatus being poorly adapted to the research, the photographic plates registered stars in such poor focus that no measurements were possible.

The measurements of the Lick plates by Campbell and Trumpler (*Lick Observatory Bulletin,* No. 346) are of the high precision one naturally expects in work emanating from the Lick Observatory. The methods adopted were the same as those of the British astronomers in 1919 and the Canadians in 1922 and consisted essentially in comparing each of the eclipse plates with a check plate of the same stellar region but with the sun absent. The most important sources of error that could influence the results were:

1. Distortions of the star places by the optical parts of the apparatus.

2. Disturbing effects in measuring the star images of the eclipse plates on account of being superimposed on the background of the corona.

3. Systematic distortion in the film of the eclipse photographs. Ross [1] of the Eastman Kodak Co. has shown that the blackened part of the corona should dry more quickly than the balance of the plate, possibly resulting in a contraction of the film towards the inner corona.

4. Abnormal refraction [2] in the earth's atmosphere on account of the cooler temperature inside the shadow-cone of the moon.

5. Refraction [3] in an extended solar atmosphere.

6. A "yearly refraction" suggested by Courvoisier.[4]

Unfortunately, the stars surrounding the sun were very weak at the 1922 eclipse, there being only two stars brighter than the ninth magnitude within 1° of the sun's center, while in 1919 there were seven stars brighter than the sixth magnitude in a similar area. It was necessary to prolong the exposures to secure as faint stars as possible. Exposures of 2 mins. and 2 mins. 5 secs. respectively, were given for each of the Einstein cameras. During totality two plates were secured with each camera, there being two cameras of 15-foot and two of 5-foot focus, the exposures starting 10 sec. after the beginning and stopping 10 sec. before the end of totality. The check plates secured in the night skies in Tahiti were given exposures of three minutes. The results given below are those from the measures of the four plates with the 15-foot camera (ratio of aperture to focal length

[1] *Astrophysical Journal, 52,* 98, 1920.
[2] A. Anderson, *Nature, 104,* 1919–20; Poor, *Science, 57,* 613, 1923.
[3] H. F. Newall, *Monthly Notices, 80,* 22, 1919.
[4] *Beob. Ergebn. Sternw. Berlin, 15,* 1913; *A. N., 211,* 205, 1920.

1:36). Stars of photographic magnitude 10.5 showed measurable images, the first time in the history of eclipse work that such faint stars have been photographed. In the process of the work the positions of 118 separate stars altogether were measured, while about 50,000 settings were necessary to accomplish this.

The star images on the eclipse plates were round and symmetrical. The present writer has found in his experience in measuring stellar photographs that a fogging of the plates by daylight, moonlight, or other causes, renders the edges of the star images ill-defined and fuzzy in appearance; consequently, one is not surprised to learn from the Lick report that the stars on the eclipse plates were not as sharp in appearance as those on the check photographs. The focus, however, was of the very best.

The details of the measurements and reductions cannot be given here. It was necessary to correct the measures for the effects of proper motion and annual parallax of the stars, for differential refraction and aberration, and for the inclination of the plates to the optical axis. Ten stars of the eclipse field and three of the auxiliary check field had proper motions of known amount and of sensible size. One star (Beta Virginis) has a measured parallax of 0″.10, and three other stars had hypothetical parallaxes which were derived from their known spectral classes and proper motions.

Arranging the stars according to their distances from the sun's center, the group means were formed and are given in the following table:

GROUP MEANS OF OBSERVED RADIAL DISPLACEMENTS

Group	*Stars*	*Mean Dist. from Sun*	*Observ'd rad. displ.*	*Correct'd rad. displ.*	*Einstein Theory*
		°	″	″	″
1	8	0.64	+.64	+.69	+.70
2	11	1.06	+.35	+.46	+.37
3	10	1.40	+.30	+.39	+.24
4	8	1.66	+.16	+.22	+.17
5	9	1.90	+.17	+.21	+.13
6	8	2.00	+.15	+.17	+.11
7	11	2.22	+.08	+.08	+.08
8	13	2.55	—.09	—.14	+.02
9	14	2.97	—.04	—.08	—.03

It is at once noticeable that the measures are in remarkable agreement with the values predicted from the Einstein theory; even the stars, far removed from the sun's center and well outside the region of the denser corona, showing the light-deflections well marked.

The Einstein deflections are inversely proportional to the angular distance from the sun's center, and reducing the values for the separate stars to the amount at the sun's limb, then there results for the four pairs of plates the values given below:

LIGHT DEFLECTION AT THE SUN'S LIMB

Pair	*Campbell*	*No. of Stars*	*Trumpler*	*No. of Stars*	*Plate Mean*
1	1″.72±″.32	62	1″.88±″.27	69	1″.80
2	1.35 .22	77	1.62 .22	81	1.48
3	1.78 .22	80	1.91 .19	84	1.89
4			1.76 .22	85	1.76
Mean for each observer	1″.60±″.14		1″.78±″.11		
Mean from four plates					**1″.72±″.11**
Einstein value					1″.745

In addition, the star field was divided into four quadrants so that the sun's equator passed through the middle of two of the quadrants and the sun's axis of rotation through the other two. The stars in each quadrant were solved separately by least squares with the results below:

Quadrant	*No. of Stars*	*Light deflection at Sun's limb*
Preceding sun's equator	24	1″.61±″.28
Following sun's equator	29	1.68 .25
At sun's north pole	18	1.76 .26
At sun's south pole	21	1.73 .24
Mean of equatorial quadrants	53	1.63 .15
Mean of polar quadrants	39	1.76 .18
Mean of plates	92	1.72 .11

The magnificent results obtained by Campbell and Trumpler at the 1922 eclipse furnish unmistakable evidence that there is a bending of the light rays from the stars as these rays pass close to the edge of the sun. The amount of

the deflection agrees remarkably closely with that predicted by the Einstein theory. The careful methods of the Lick astronomers, both in the taking of the plates and the measurement of them, seem to indicate that all possible sources of error have either been eliminated or been allowed for. There remains the observed deflection of $1''.72$ at the sun's limb to be explained. This value would appear to furnish a complete confirmation of the theory of relativity were it not for some facts which must be noted:

1. Einstein's theory is not the most generalized form, and there are some uncertainties still existing among mathematical physicists regarding the size of the angle of deflection to be expected from the theory, Larmor believing that the angle should be half the size of Einstein's expectation.

2. Although the relativity theory explains the motion of the perihelion of Mercury, it does not explain, and leaves still untouched, many discordances from the Newtonian law of gravitation.

3. The shift of wave-lengths in the solar spectrum demanded by the Einstein theory has not yet been verified.

4. In the repetition of the famous Michelson-Morley experiment by Miller, certain unexplained deflections of minute size have been repeatedly observed. Until the causes of these deflections are traced to their source, the theory of relativity is based upon an insecure foundation.

5. On the basis of the relativity theory it is difficult to explain an observation made by Airy many years ago that there is no change in the constant of aberration when a beam of light passes through water (where the velocity of light is smaller) instead of through air.

A theory of such great importance to modern scientific thought needs confirmation at more than one eclipse. The present writer regrets that the Lick Observatory has not this same problem on its program for the 1923 eclipse. Fortunately, other astronomers will continue the attack, for no doubt it will be many years in the future before astronomers and physicists are agreed on the exact status of the theory of relativity.

The American astronomers have made an excellent record

of splendid results accomplished during the fleeting moments of the total phases of solar eclipses. If they are to maintain their enviable reputations for the successful observations of eclipses it will be necessary, after the eclipses of 1923 and 1925 have passed into memory, for them to travel long distances from home in order to secure their observational material.

The author hopes that he has been able to indicate why astronomers have been so eager to observe total eclipses in the past, what is the approximate status of our present knowledge from a study of these eclipses, and what problems of importance still await solution in the future.

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ECLIPSES OF THE SUN

MITCHELL